

Polypropylene

The Definitive User's Guide and Databook

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Manufactured in the United States of America.

Polypropylene is a versatile thermoplastic material, compatible with many processing techniques and used in many different commercial applications. [797] It is one of the fastest growing classes of commodity thermoplastics, with a market share growth of 6–7%/year, and the volume of polypropylene produced is exceeded only by polyethylene and polyvinyl chloride. [794, 790]

The moderate cost and favorable properties of polypropylene contribute to its strong growth rate. It is one of the lightest of all thermoplastics (0.9 g/cc), so that fewer pounds are required for finished parts. Due to its high strength-to-weight ratio, it is more rigid than other polyolefins. It has the highest melting temperature (160–170°C; 320–338°F) of all commodity thermoplastics and better heat resistance than other low-cost thermoplastics; unmodified polypropylene, however, becomes brittle at subambient temperatures. [696, 794]

Its excellent chemical resistance includes resistance to most organic solvents, except for very strong oxidizing agents; however, softening may occur due to the permeation of chlorinated solvents and hydrocarbons. Its good fatigue resistance makes it widely used in “living hinge applications” — in testing, oriented thin sections can withstand more than one million repeated flexings. It is usually not susceptible to environmental stress cracking. Its clarity is greater than that of other polyolefins, and many grades can withstand commonly used sterilization methods. [696, 699]

Polypropylene is available in a wide variety of melt flow rates, ranging from 0.3 to over 1000 g/10 min., and it is easily recycled. It can be processed by virtually all methods, including injection molding, blow molding, extrusion, blown and cast film, and thermoforming. [795, 794, 797, 796, 693]

Many available grades with different properties make polypropylene useful in applications such as fibers, films, filaments, and injection molded parts for automobiles, rigid packaging, appliances, medical equipment, food packaging, and consumer products. It is being substituted for glass, metal, and engineering plastics such as ABS, polycarbonate, polystyrene, and nylon in kitchen appliances and large appliances such as ovens, dishwashers, refrigerators, and washing machines, and high flow grades are used in molding large housewares. Su-

per-soft grades are replacing polyvinyl chloride in medical bags and tubing and in hospital gowns. [797, 791, 793, 792, 696, 776]

Polypropylene — The Definitive User's Guide provides detailed information on the science and technology of polypropylene. The book includes chapters on the chemistry and morphology of polypropylene, common additives and fillers, and design and processing. Detailed discussions of injection molding, extrusion, blow molding, thermoforming, and fabricating polypropylene are presented in separate chapters. Descriptions of common product forms — foams, fibers, films, and sheets — are provided, in addition to commercially available forms of resins: homopolymer and random and impact copolymers. In other chapters, the many applications of polypropylene, recycling methods, and the safety and health aspects of polypropylene in use and processing are described. Properties and characteristics of polypropylene and the effect of chemistry, morphology, and processing on these characteristics are discussed.

Other sections contain extensive lists of data sheet properties for representative, commonly used grades of polypropylene and an extensive compilation of data in tabular and graphical form that includes creep data, stress-strain data, fatigue, effect of UV light and weathering, effect of sterilization methods, film properties, temperature-mechanical property relationships, composition-mechanical property relationships, temperature-thermal property relationships, stress relaxation data, viscosity data, data on thermodynamic properties, and chemical and environmental stress crack resistance. Each table or graph is designed to stand alone, be easy to interpret, and provide all relevant and available details of test conditions and results.

This publication serves to turn the vast amount of disparate information from wide ranging sources (i.e., conference proceedings, materials suppliers, test laboratories, monographs, and trade and technical journals) into useful engineering knowledge. Although substantial effort is exerted throughout the editorial process to maintain accuracy and consistency in presentation of information, the possibility for error exists. Often these errors occur due to insufficient or inaccurate information in the source document.

How a material performs in its end use environment is a critical consideration and the information here gives useful guidelines. However, this or any other information resource should not serve as a substitute for actual testing in determining the applicability of a particular part or material in a given end use environment.

Although the book contains information and data from many sources, the information is arranged to be easily accessible to readers; flexibility and ease of use were carefully considered in designing the layout of this book. It is organized so that information of interest, whether general information or detailed test data, can be quickly found, using the general index, the index of figures, the index of tables, the detailed table of contents, or the numerous sub-headings within each chapter. For readers who wish to delve beyond the

data presented, detailed source documentation is provided in the reference index; for those for whom polypropylene is a relatively new field, the glossary of terms will prove useful.

We trust you will greet this reference publication with the same enthusiasm as previous Plastics Design Library titles and that it will be a useful tool in your work. As always, your feedback on improving this volume or others in the PDL Handbook series is appreciated and encouraged.

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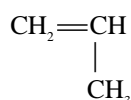
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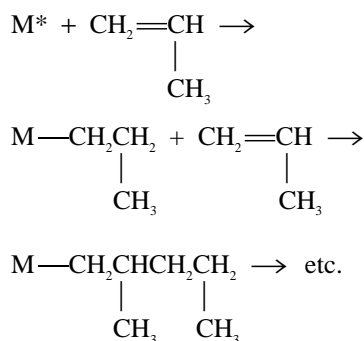
1.1 Polymerization reaction

Polypropylene is prepared by polymerizing propylene, a gaseous byproduct of petroleum refining, in the presence of a catalyst under carefully controlled heat and pressure. [773] Propylene is an unsaturated hydrocarbon, containing only carbon and hydrogen atoms:



Propylene

In the polymerization reaction, many propylene molecules (monomers) are joined together to form one large molecule of polypropylene. Propylene is reacted with an organometallic, transition metal catalyst (see 1.4 Catalysts for a description of catalysts used in the reaction) to provide a site for the reaction to occur, and propylene molecules are added sequentially through a reaction between the metallic functional group on the growing polymer chain and the unsaturated bond of the propylene monomer:



One of the double-bonded carbon atoms of the incoming propylene molecule inserts itself into the bond between the metal catalyst (M in the above reaction) and the last carbon atom of the polypropylene chain. A long, linear polymer chain of carbon atoms is formed, with methyl (CH₃) groups attached to every other carbon atom of the chain (Figure 1.1). Thousands of propylene molecules can be added sequentially until the chain reaction is terminated. [764, 768]

1.2 Stereospecificity

With Ziegler-Natta or metallocene catalysts, the polymerization reaction is highly stereospecific. Propylene molecules add to the polymer chain only in a particular orientation, depending on the chemi-

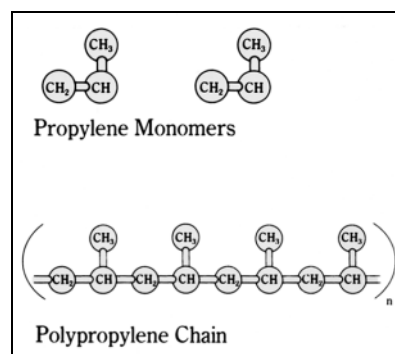
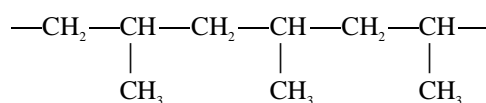
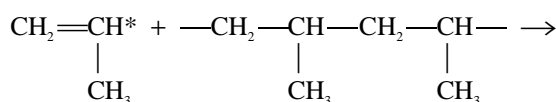
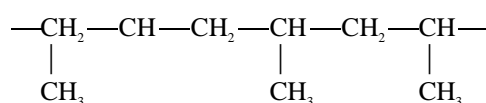
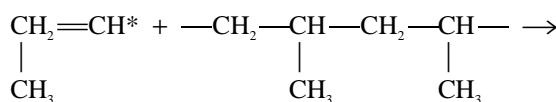


Figure 1.1 Molecules of propylene and polypropylene. In the polymerization reaction, propylene monomers (top) are added sequentially to the growing polymer chain (bottom), to form a long, linear polymer chain composed of thousands of propylene monomers. The portion of the chain shown in parentheses is repeated *n* number of times to form the polymer. [642]

cal and crystal structure of the catalyst, and a regular, repeating three-dimensional structure is produced in the polymer chain [763]. Propylene molecules are added to the main polymer chain, increasing the chain length, and not to one of the methyl groups attached to alternating carbon atoms (the pendant methyl groups), which would result in branching. Propylene molecules are usually added head-to-tail and not tail-to-tail or head-to-head. Head-to-tail addition results in a polypropylene chain with pendant methyl groups attached to alternating carbons; in tail-to-tail or head-to head addition, this alternating arrangement is disrupted. [771]



Head-to-tail addition of propylene to the growing polypropylene chain



Tail-to-tail addition of propylene to the growing polypropylene chain

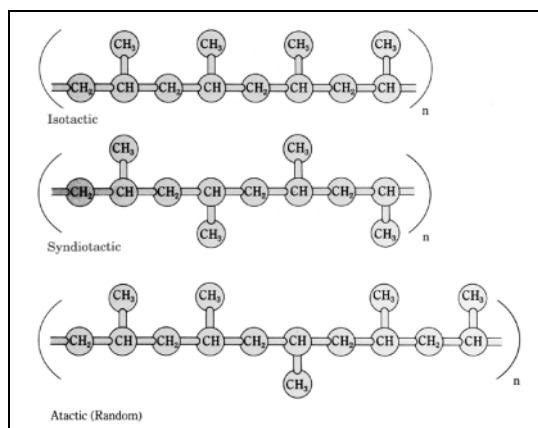


Figure 1.2 Stereochemical configurations of polypropylene. In isotactic polypropylene, top, the pendant methyl groups branching off from the polymer backbone are all on the same side of the polymer backbone, with identical configurations relative to the main chain. In syndiotactic polypropylene, middle, consecutive pendant methyl groups are on opposite sides of the polymer backbone chain. In atactic polypropylene, bottom, pendant methyl groups are oriented randomly with respect to the polymer backbone. The portion of the chain shown is repeated n number of times to form the polymer. [642]

Occasional tail-to-tail or head-to-tail additions of polypropylene to the growing polymer chain disrupt the crystalline structure and lower the melting point of the polymer; formulations in which this occurs are used in thermoforming or blow molding. [694]

Polypropylene can be isotactic, syndiotactic, or atactic, depending on the orientation of the pendant methyl groups attached to alternate carbon atoms. In isotactic polypropylene (Figure 1.2), the most common commercial form, pendant methyl groups are all in the same configuration and are on the same side of the polymer chain. Due to this regular, repeating arrangement, isotactic polypropylene has a high degree of crystallinity. In syndiotactic polypropylene, alternate pendant methyl groups are on opposite sides of the polymer backbone, with exactly opposite configurations relative to the polymer chain. Syndiotactic polypropylene is now being produced commercially using metallocene catalysts. In atactic polypropylene, pendant methyl groups have a random orientation with respect to the polymer backbone. Amounts of isotactic, atactic, and syndiotactic segments in a formulation are determined by the catalyst used and the polymerization conditions. Most polymers are predominantly isotactic, with small amounts of atactic polymer. New metallocene catalysts make possible other stereochemical configurations, such as hemi-isotactic polypropylene. In this configuration, most pendant methyl groups are on the

same side of the polypropylene chain, as in isotactic polypropylene; however, other methyl groups are inserted at regular intervals on the opposite side of the chain. [794, 695, 810]

1.3 Effect on characteristics of polypropylene

The structure and stereochemistry of polypropylene affect its properties.

1.3.1 Stereochemistry

Because of its structure, isotactic polypropylene has the highest crystallinity, resulting in good mechanical properties such as stiffness and tensile strength. Syndiotactic polypropylene is less stiff than isotactic but has better impact strength and clarity. Due to its irregular structure, the atactic form has low crystallinity, resulting in a sticky, amorphous material used mainly for adhesives and roofing tars. [794, 691] Increasing the amount of atactic polypropylene in a predominantly isotactic formulation increases the room temperature impact resistance and stretchability but decreases the stiffness, haze, and color quality. [695] The amount of atactic polypropylene in a polypropylene formulation is indicated by the level of room temperature xylene solubles; levels range from about 1–20%. [771] Polypropylenes generally have higher tensile, flexural, and compressive strength and higher moduli than polyethylenes due to the steric interaction of the pendant methyl groups, which result in a more rigid and stiff polymer chain than in polyethylene. [693] General effects of atactic level on the properties of polypropylene are listed in Table 1.1. [695, 642, 693]

1.3.2 Molecular weight and melt flow index

Longer polypropylene chain lengths result in a higher molecular weight for the polymer. The weight-average molecular weight of polypropylene generally ranges from 220,000–700,000 g/mol, with melt flow indices from less than 0.3 g/10 min. to over 1000 g/10 min. The melt flow index (MFI) provides an estimate of the average molecular weight of the polymer, in an inverse relationship; high melt flow indicates a lower molecular weight. [693, 642, 696, 797]

Viscous materials with low MFI values (<2) are used in extrusion processes, such as sheet and blow molding, that require high melt strength. Resins with MFI values of 2–8 are used in film and fiber

Table 1.1 Effect of Atacticity on Polypropylene Properties

Property	With Increasing Atacticity
Stiffness	Decreases
Moduli	Decrease
Strength	Decreases
Room Temperature Impact Resistance	Increases
Stretchability	Increases
Elongation	Increases
Shear Rheology	Increases
Long Term Heat Aging (LTHA) Resistance	Decreases
Heat Distortion Temperature	Decreases
Heat Seal Strength	Increases
Haze in Films	Decreases
Blocking in Films	Increases
Irradiation Tolerance	Increases
Extractables (solubility)	Increase
Smoke and Fume Generation	Increases
Color Quality	Decreases
General Optical Properties	Increase
Melting Temperature	Decreases
Heat of Fusion	Decreases
Crystallization Temperature	Decreases

applications, and materials with MFI values of 8–35 or more are used in extrusion coating, injection molding of thin-walled parts that requires rapid mold filling, and fiber spinning. [642]

The toughness of a grade of polypropylene is directly related to molecular weight: higher molecular weights provide greater toughness. As a result, higher molecular weight polypropylenes have greater impact resistance and elongation and less brittleness. [693, 642, 696] General effects of increasing molecular weight on polypropylene properties are summarized in Table 1.2. [693]

1.3.3 Molecular weight distribution

A polypropylene resin is composed of numerous chains of varying lengths, with varying molecular weights. The molecular weight distribution (MWD) indicates the variation of molecular weight in a particular formulation; the MWD is narrow if most molecular chains are approximately the same length and broad if the chains vary widely in length (Figure 1.3).

Table 1.2 Effect of Increasing Molecular Weight on Properties of Polypropylene

Property	With Increasing Molecular Weight
Impact Resistance	Increases
Elongation	Increases
Moduli	Decrease
Strength	Decreases
Die Swell	Increases
Shear Rheology	Increases
Melt Strength	Increases
Heat Seal Strength	Increases
Heat Distortion Temperature	Decreases
Irradiation Tolerance	Decreases
Haze	Decreases
Extractables (solubility)	Decreases
Crystallization Temperature	Decreases

Molecular weight distribution, measured as the ratio of weight-average molecular weight to number-average molecular weight (M_w/M_n) can vary from 2.1 to over 11.0. The number-average molecular weight is related to the number of polymer chain molecules at a particular molecular weight, while the weight-average molecular weight relates to the mass (or weight) of the polymer chain molecules at a particular molecular weight. [642, 691, 795]

The MWD influences the processability of a resin due to the shear sensitivity of molten polypro-

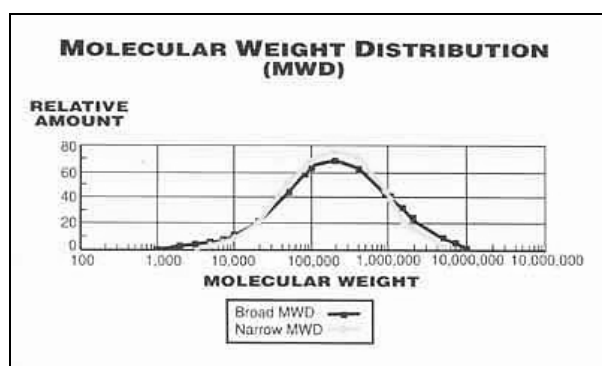


Figure 1.3 Graph of broad and narrow molecular weight distributions in polypropylene. In a resin with a narrow molecular weight distribution, polymer chains have approximately the same length and therefore the same molecular weight. The frequency of occurrence of these molecular weight chains is high, resulting in a narrow, high peak. A resin with a broad molecular weight distribution consists of polymer chains of varying lengths and molecular weights, resulting in a broad molecular weight distribution. The frequency of occurrence of any particular molecular weight is low, producing a low, broad peak.

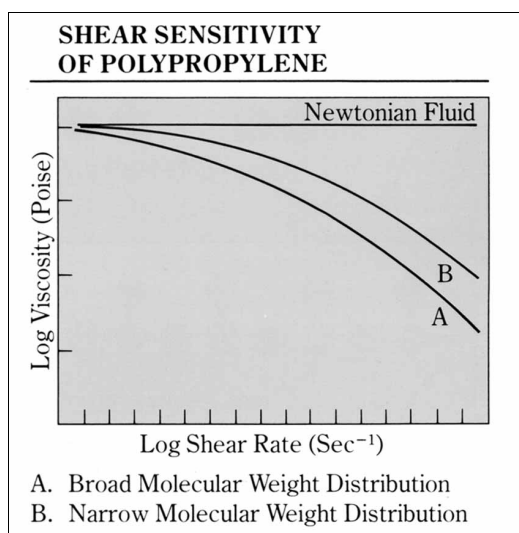


Figure 1.4 Influence of the molecular weight distribution of a polypropylene resin on shear sensitivity.

In a Newtonian fluid, such as water, the viscosity of the fluid is constant with varying shear strain. In molten polypropylene, a shear sensitive material, the viscosity varies with the rate of shearing strain. A polypropylene resin with a broad molecular weight distribution, A, is more shear sensitive than a resin with a narrow molecular weight distribution, B. [642]

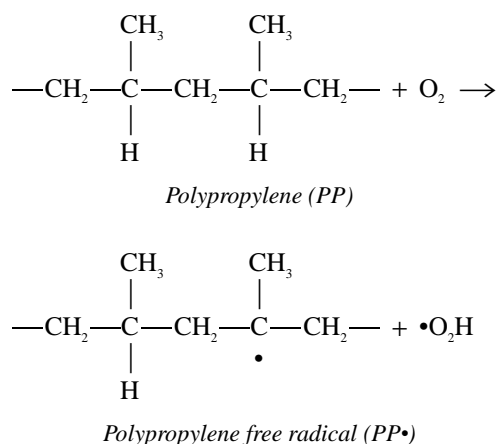
polyene — the apparent viscosity decreases as the applied pressure increases. Because a polypropylene resin with a broad MWD is more shear sensitive than a narrow MWD formulation (Figure 1.4), materials with broad MWD's are processed more easily in applications such as injection molding. Polypropylene resins with narrow MWD's are used in extrusion, in which a narrower MWD generally results in a higher achievable extrusion output rate [694], or in applications such as fibers. [642]

1.3.4 Oxidation

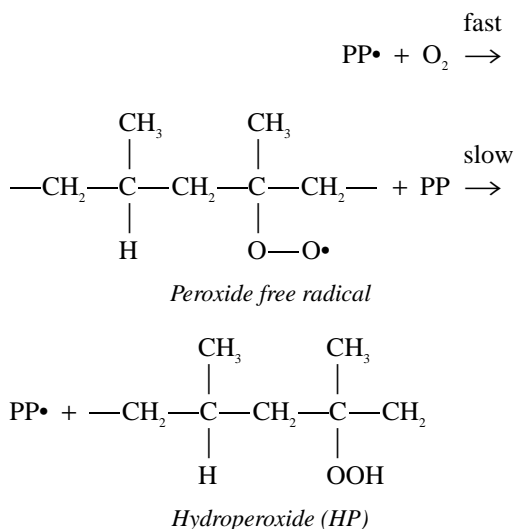
Polypropylene is highly susceptible to oxidation due to the presence of the tertiary hydrogen on the carbon atom bonded to the pendant methyl group. Polypropylene undergoes oxidation more readily than polyethylene, and oxidative chain scission, which reduces the molecular weight, occurs under normal processing conditions if the resin is not stabilized. [794, 795]

Polymer oxidation occurs through a free radical chain reaction. Mechanical stress, heat, or the presence of oxygen or metal catalyst residues results in homolytic cleavage of the carbon-hydrogen or carbon-carbon covalent bond in the polypropylene chain; each atom receives one electron from the two-electron covalent bond, producing two free radicals, each with an unpaired

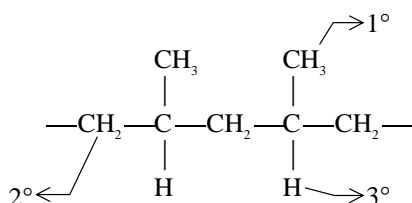
electron. An example of a chain initiation reaction in the presence of oxygen is given below:



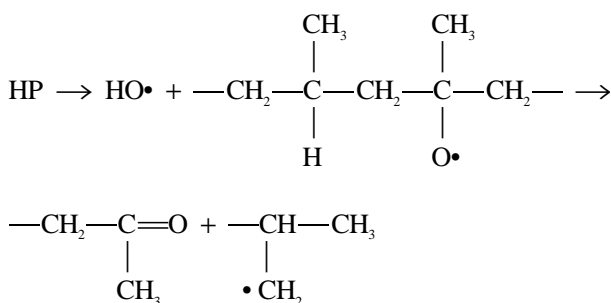
The chain reaction is propagated through the formation of a hydroperoxide, accompanied by the formation of another free radical:



The oxidation rate is determined by the rate of the slow step in the chain propagation reactions. Due to the presence of the pendant methyl group, polypropylene contains tertiary (3°) hydrogen atoms, in which the carbon atom covalently bonded to the hydrogen is also bonded to three other carbon atoms. The free radical (PP•) formed from abstraction of a tertiary hydrogen is more stable than those formed from abstraction of a primary (1°; carbon atom attached to one other carbon) or secondary (2°; carbon atom attached to two other carbons) hydrogen, due to the tendency of carbon atoms along the chain to electronically donate electrons to the electron-deficient radical. The higher probability of reaction with the tertiary hydrogen considerably increases the susceptibility of polypropylene to oxidation. [768, 817]



In further reactions (chain branching reactions that increase the amount of free radicals), the hydroperoxide decomposes in the presence of heat or metal catalyst residues to form an alkoxy radical. Oxidative chain scission is believed to occur through disintegration of this alkoxy radical:



The decrease in molecular weight resulting from chain scission produces a gradual loss in mechanical properties. Crosslinking, which is common in polyethylene oxidation, producing an increase in viscosity, does not occur frequently in polypropylene due to preferential oxidative attack at the tertiary hydrogen, which leads to chain scission. Compounds such as carboxylic acids, lactones, aldehydes, and esters are also produced during oxidation reactions, resulting in chemical modifications such as yellowing. Chain reactions are terminated when two radicals combine to form an inactive species. [817, 818]

1.3.5 Electrical conductivity

Electrically conductive materials, such as metals, have delocalized electrons that can easily move along a potential gradient. Electrons in the covalent bonds of organic molecules such as polypropylene must remain near their host atoms and are not free to move through the material; as a result, they are poor conductors of electricity. [782] The high dielectric strength and low dielectric constant and dissipation factor of polypropylene make it useful as an insulating material. [783, 642] Conductive materials such as carbon black can be added to a polypropylene formulation for applications requiring electrical conductivity. [698]

1.3.6 Chemical resistance

Because it is composed of only carbon and hydrogen atoms, and not polar atoms such as oxygen or nitrogen, polypropylene is nonpolar. Nonpolar molecules are generally soluble in nonpolar solvents, while polar molecules are more soluble in polar solvents ("like dissolves like"); as a result, nonpolar molecules are more easily absorbed by polypropylene than polar molecules. Polypropylene is resistant to attack by polar chemicals such as soaps, wetting agents, and alcohols but can swell, soften, or undergo surface crazing in the presence of liquid hydrocarbons or chlorinated solvents. Strong oxidizing agents such as fuming nitric acid or hot, concentrated sulfuric acid can cause swelling and polypropylene degradation. A large degree of absorption can cause a loss of physical properties. [642, 795]

1.4 Catalysts

The development of catalysts for polypropylene polymerization in the 1950's made the production of stereospecific polypropylene possible and led to the rapid growth rate of polypropylene that is still occurring today. Catalysts are substances that increase the rate of a reaction but undergo no permanent chemical change themselves. In polypropylene polymerization, catalysts are organometallic transition metal complexes. They provide active sites or polymerization sites where the polymerization reaction occurs, by holding the growing polymer chain and the propylene monomer in close proximity to each other so that they can react. With commercial catalysts, a high yield of stereospecific polypropylene is produced.

1.4.1 Ziegler-Natta catalysts

Ziegler-Natta catalysts are the most common commercial catalysts. Karl Ziegler and Giulio Natta jointly received the Nobel Prize in 1963 for the development of polyolefin polymerization catalysts with high yield and a high degree of stereospecificity. The original Ziegler-Natta catalysts were a complex of transition metal halides, usually titanium trichloride (TiCl₃), with an organometallic compound, typically triethylaluminum, as co-catalyst to initiate the polymerization. Yield of isotactic polypropylene in these original catalysts was low, 30–40%, but was rapidly increased to over 80% with further development. [768, 788] Due to the low isotacticity, postreactor treatment

was necessary in order to remove catalyst residues and atactic material. [695]

Catalyst improvements have led to increased stereospecificity and productivity. The low surface areas of early TiCl_3 catalysts resulted in low catalyst activity; since only titanium atoms on the catalyst surface are accessible to the organo-metallic compound, few active sites were formed, and the amount of polypropylene produced per gram of catalyst used was low. TiCl_3 catalysts with increased surface areas resulted in increased productivity and isotacticity (~95%). [764]

Supported heterogeneous Ziegler-Natta catalysts were developed in the 1960's, with magnesium chloride (MgCl_2) used as the inert support material. Heterogeneous catalysts are present in a different phase (solid, liquid, gas) from the reaction mixture; they are fixed onto the surface of a support material for feeding into the reactor during processing and for control of polymer growth. Addition of a Lewis base, typically a benzoic acid ester, as an electron donor (internal donor) and a second Lewis base (methyl-p-toluate) as an external donor to the MgCl_2 -supported catalyst increased catalyst activity and stereospecificity and eliminated the necessity of post reactor removal of catalyst residues. [604, 764, 758]

Catalyst systems using newer Lewis bases (alkylphthalates and alkoxysilanes as internal and external donors, respectively) further increased isotacticity and activity and are currently used in the industrial production of polypropylene. Catalyst systems using new internal electron donors, developed in the latter part of the 1980's, result in very high activity and isotacticity without use of an external electron donor. They are not yet in industrial use. [764, 758]

1.4.2 Characteristics of polypropylene produced using Ziegler-Natta catalysts

Ziegler-Natta catalysts are multi-sited catalysts, containing several reactive sites. As a result, the polypropylene produced can include polymer molecules with a broad range of molecular weights and some branching off from the main polymer chain. [759] For film and fiber applications and for injection molding of thin walls or parts with intricate structures, a narrower molecular weight distribution and increased melt flow rate may be required. For these applications, the polypropylene produced must be chemically or thermally broken down in post-reactor extrusion. [694, 794]

Chemical breakdown of the polymer chains is accomplished by oxidative chain degradation initiated by a peroxide, a process called controlled rheology (CR) or visbreaking. This process shortens the average length of the polymer chains, lowers the molecular weight, and narrows the molecular weight distribution, resulting in lower melt viscosity, increased flow rates, and slightly enhanced impact strength. Molding cycles can be up to 15% faster than with conventional grades, and warpage and shrinkage are reduced. [794, 696, 691, 693, 765]

Metal catalyst residues that remain in the polypropylene resin may affect the opacity of the resin, and resins made using different catalysts may have different levels of clarity. In addition, additives can interact with catalyst residues to produce yellowness. [692]

1.4.3 Metallocene catalysts

Metallocene catalysts have recently been developed for industrial use, and metallocene-produced polypropylene is now available. In contrast to Ziegler-Natta catalysts, metallocene catalysts are single-sited — they have identical active sites — and properties such as molecular weight and stereostructure can be tailored to meet the needs of the application. [694, 758, 781] Syndiotactic polypropylene is now being produced commercially using metallocenes; commercial production was not possible with Ziegler-Natta catalysts. [794]

Metallocenes are organometallic compounds with a sandwich-like spatial arrangement, consisting of a transition metal (iron, titanium, zirconium) situated between two cyclic organic compounds (Figure 1.5). [767] Geoffrey Wilkinson and Ernst O. Fischer received the Nobel prize in chemistry for elucidation of the structure of ferrocene, one of the first metallocenes discovered. [654] The first metallocenes used for polymerization, titanocenedichloride and an aluminum alkyl such as trimethylaluminum, showed poor activity and were used only in scientific studies. [758, 654] However, in 1975, accidental introduction of water into a test tube containing a metallocene catalyst system and ethylene increased the polymerization rate 1000 times and led to the development of methylalumoxane (MAO), a product of the partial hydrolysis of trimethylaluminum, as a catalyst activator or cocatalyst. [758, 654]

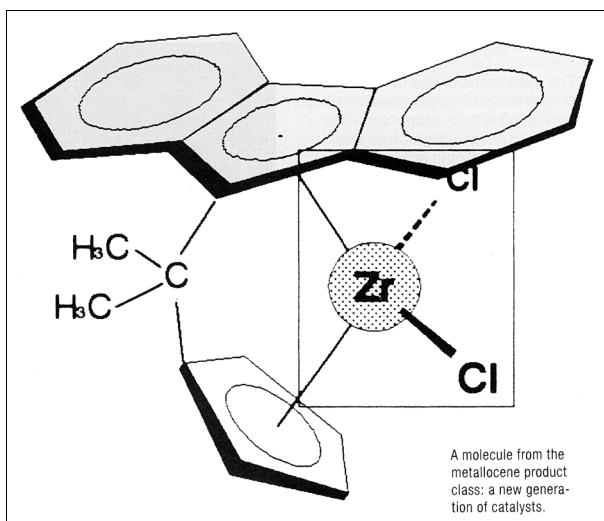


Figure 1.5 Structure of one type of metallocene catalyst. A zirconium atom is bound to two chlorine atoms and to a bridged alkyl group. The $ZrCl_2$ complex is located in a cleft formed by the alkyl group; the polymerization reaction occurs in the cleft. The molecule is represented in three dimensions — the dotted line indicates that one chlorine is located behind the plane of the paper, while the heavy bold line to the other chlorine indicates that it is located in front of the plane of the paper. [182]

The introduction of chiral, bridged metallocenes using first titanium, then zirconium, in the 1980's allowed the stereoselective polymerization of propylene to isotactic polypropylene. In bridged metallocenes, a molecular “bridge” connects the two organic compounds of the metallocene “sandwich”. A chiral molecule is one that, in its three dimensional configuration, cannot be superimposed on its mirror image. In 1988, syndiotactic polypropylene was synthesized using zirconium-containing metallocenes. [654, 767]

Current metallocene catalyst systems commonly use zirconium chloride ($ZrCl_2$) as the transition metal complex, with a cyclopentadiene as the organic compound and an aluminoxane such as MAO as co-catalyst. Polypropylene resins with varying micro-

structures, molecular weights, and other properties can be produced by varying the transition metal and organic compound used. [764, 654]

Metallocene polymerization in the laboratory makes use of homogeneous catalysis; catalysts and reacting materials are in solution. For large-scale industrial processes, metallocenes must be fixed or supported on powdery, insoluble substrates; SiO_2 , Al_2O_3 , or $MgCl_2$, are generally used. A polypropylene chain is synthesized on each grain of powder, and because active sites on each grain are identical, the chains grow to a uniform length. [692, 654]

1.4.4 Characteristics of polypropylene produced using metallocene catalysts

Polypropylenes made using metallocene catalysts exhibit increased rigidity and transparency, higher heat distortion temperatures, improved impact strength and toughness even at subambient temperatures, and low extractables. [760, 654] Due to the uniformity of the polypropylene chains, metallocene-catalyzed propylene has a very narrow molecular weight distribution (Mw/Mn of 2.0) compared to conventional polypropylene (minimum Mw/Mn of 3–6). The narrow MWD results in lower shear sensitivity of the polypropylene resin and provides low melt elasticity and elongational viscosity in extrusion processes. [694]

The melting point (147–158°C; 297–316°F) of metallocene polypropylene currently produced is generally lower than that of conventional polypropylene (160–170°C; 320–338°F) and can be tailored to a specific application by using the appropriate metallocene as catalyst. [654, 694] As with Ziegler-Natta catalysts, resin color is affected by the type and amount of catalyst residue present, and interaction with additives may cause yellowing. [692]

2 Morphology and Commercial Forms

When cooled to temperatures below the melting point (the crystallization temperature), polypropylene molecules associate to form supramolecular structures. Polypropylene is a semicrystalline polymer; varying degrees of crystallinity and different types of crystal structures are possible, depending on the stereochemical structure, the processing or crystallization conditions, and the presence of additives.

Crystallinity arises from the stereoregularity in the molecular structure; occasional irregularities such as branching or tail-to-tail addition during polymerization or the presence of copolymers limit the extent of crystallization. [769] Atactic polypropylene, with its random, irregular molecular structure, is predominantly amorphous. Semicrystalline polymers have high strength, stiffness, and density and sharp melting points. Amorphous polymers are tough and ductile, with higher impact strength, lower density, and lower haze. [772, 693] Properties of a polypropylene resin can be adjusted, depending on processing conditions and catalysts, by varying the level of crystallinity in the polymer. [797]

Polymer crystallization occurs when melted material solidifies or when the solvent is evaporated. As heat is removed from the melt during processing, molecules begin to lose the ability to move freely, and the melt becomes more viscous. At the crystallization temperature, molecules begin to arrange themselves into crystals, and ordered crystalline regions are formed, along with disordered amorphous regions. Crystal growth may be spontaneous (when the molecular structure is favorable to a highly ordered structure) or may be induced by the presence of a foreign particle (such as a nucleating agent or the metal mold surface). [772, 769] The crystallization rate is dependent on the nucleation rate and the rate of crystal growth; as the melt becomes cooler, the nucleation rate increases, while the rate of crystal growth decreases. The optimum crystallization rate usually occurs at a temperature equal to about 0.8 times that of the melting temperature. Crystallization is generally favored by slower cooling from the melt, and the degree of crystallization can be controlled by the rate of melt quenching and subsequent annealing. Very rapid cooling can suppress crystallization. [774, 772, 891]

2.1 Crystal structure and microstructure

The smallest crystal unit is the unit cell, with dimensions of angstroms (\AA). Unit cells are geometrical shapes with parallel sides (i.e. tetragonal, cubic, hexagonal) that represent the placement of atoms. The atomic arrangement in the unit cell of a polymer is repeated millions of times in three-dimensional space in forming the crystalline structure. [604, 782].

The polymer chain in polypropylene forms a helical arrangement, reminiscent of a winding staircase, as it crystallizes, due to the presence of the pendant methyl group. Polymers with closely spaced bulky groups form a helix in order to pack atoms closely together without distortion of the bonds along the chain. [769]

The helical chains fold back and forth to form thin, ordered, plate-like or ribbon-like structures called lamellae. Typical lamellae are 20–500 \AA in thickness and $\sim 10^5$ \AA in lateral dimensions; thickness depends on crystallization temperature and processing methods. The plate-like lamellae stack side-by-side, with distances of 100–300 \AA between them. Lamellae that grow in a radial direction form spherulites, spherical structures that radiate outward from a central nucleus, as in a pom-pom. [703, 769, 772, 730, 526]

Lamellae are connected by amorphous regions, called “tie points”, that result from irregularities in the polymer chain. Tie points provide flexibility and impact resistance to the crystalline regions. A polymer with more tie points is generally stronger; however, too many tie points can result in brittleness, low

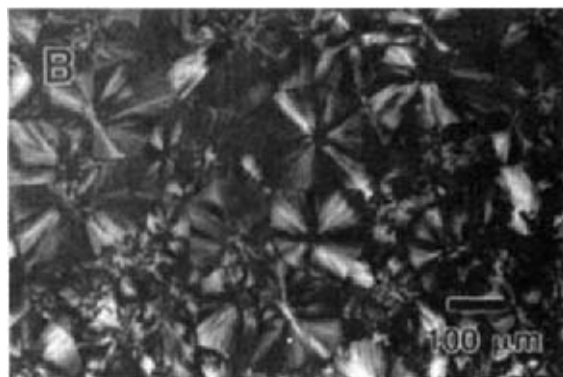


Figure 2.1 A Maltese cross pattern of birefringence obtained using optical microscopy under crossed polarizers. Polypropylene was isothermally crystallized at a pressure of 100 MPa. [775]

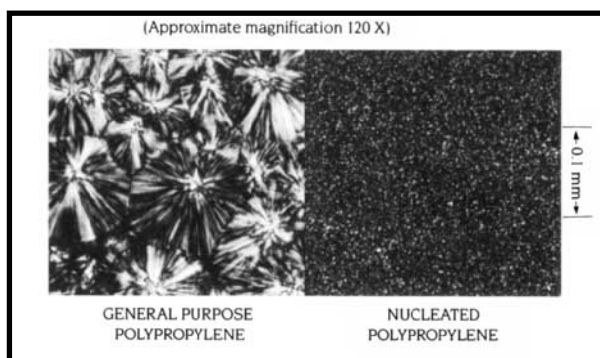


Figure 2.2 An optical micrograph showing the effect of a nucleating agent on spherulite size. In nucleated polypropylene, right, spherulites are smaller and more numerous than in unnucleated polypropylene, left. Magnification is approximately 120x.

toughness, and low impact resistance. [772, 693] When lamellae from two spherulites meet, lamellae from each spherulite extend across the boundary into any adjacent amorphous material, which tends to hold the material together. [769] If crystallization occurs rapidly, as it does in crystallization from a melt such as in injection molding, the polymer chains can crystallize within more than one lamellae. [772]

Spherulite size in polypropylene ranges from 1–50 μm . [770] Spherulites can be observed with optical microscopy under crossed polarizers as a Maltese cross pattern (Figure 2.1), consisting of a central, dark cross with wings coincident with the planes of the polarizer and analyzer. [775, 703]

The presence of a nucleating agent provides additional sites for crystal growth, resulting in smaller, more numerous spherulites in the crystallized polymer (Figure 2.2). Many organic compounds and metal salts can act as nucleating agents, including colorant pigments and residual monomer. Pigments vary in their ability to cause nucleation; green and blue pigments, such as phthalocyanine blue, appear to have the largest effect. [779, 696]

2.2 Polymorphism

Polypropylene can exist in different morphological forms, depending on the tacticity of the resin and the crystallization conditions, such as pressure, temperature, and cooling rate. Different forms can coexist, and one polymorphic form can change into another as conditions change.

2.2.1 α -form of isotactic polypropylene

Polymer chains in the α -form of isotactic polypropylene form a helical structure in a monoclinic unit cell, with dimensions of 20.8 \AA \times 6.6 \AA \times 6.5

\AA and fold into lamellae with thicknesses of 50–200 \AA . [770, 733] Radial growth of lamellae is dominant; however, lamella can also associate tangentially, with the tangential lamella branching off approximately orthogonally from the plane of the radial lamellae. This forms a cross-hatched structure in the lamellae, which aggregate to form spherulites. [775, 770]

The lamellar structure produces positive, negative, and mixed birefringence. Negative birefringence results from spherulites in which radial lamella are dominant, while positive birefringence is due to spherulites with predominantly tangential lamellae. Both negatively and positively birefringent spherulites form a Maltese cross pattern under crossed polarizers. In spherulites with mixed birefringence, neither tangential nor radial lamellae are predominant, and a distinct Maltese cross is not formed. The birefringence changes from positive to negative with increasing crystallization temperature, as the tangential lamella undergo premelting. [703, 770] The α -form of isotactic polypropylene is the primary form of polypropylene obtained under normal processing conditions. [733]

2.2.2 β -form of isotactic polypropylene

The β -form of isotactic polypropylene has a hexagonal unit cell structure, with more disorder than the α -form. The parallel, stacked lamella do not show cross-hatching. Lamella have been observed to form sheaf-like spherulitic structures with interconnected boundaries, different from the distinct boundaries of α -form spherulites; in experiments with high purity β -form polypropylene, this structure resulted in lower elastic moduli and yield strength at a given strain rate and higher impact strength and breaking strain values than α -form polypropylene. The β -form exhibits negative birefringence under crossed polarizers and can convert to the α -form on heating. Polypropylene can crystallize in the β -form at relatively low isothermal crystallization temperatures or in the presence of nucleating agents, such as the combination of pimelic acid and calcium stearate. [775, 733, 770]

2.2.3 γ -form of isotactic polypropylene

The γ -form of isotactic polypropylene was initially considered to have a triclinic unit cell with dimensions similar to the α -form, but the crystal structure was recently reassigned as an orthorhombic unit cell with nonparallel, crossed lamellae. In experiments with polypropylene crystallized at high



Figure 2.3 Reflection optical micrograph of lamellae in isotactic polypropylene arranged in feather-like structures. The polypropylene sample was crystallized isothermally at 203°C (397°F) and 200 MPa (30,000 psi) and was permanganically etched for 30 minutes. [703]

pressures and different crystallization temperatures, the crossed lamellae formed a feather-like structure (Figure 2.3) that was shown from microscopy to result from self-epitaxial (tangential) growth. [703, 770]

γ -form polypropylene does not usually form under typical processing conditions. It can occur in low molecular weight materials ($M_n \cong 6000$), during crystallization at elevated pressures, or in chains with regular defects, produced using metallocene catalysts. The α -form is present at atmospheric pressure; as the pressure is increased, the γ -form begins to coexist with the α -form until it becomes dominant at a pressure of 200 MPa (2901 psi). [775, 703, 732]

2.2.4 Syndiotactic polypropylene

The recent development of metallocene catalysts that produce highly stereospecific syndiotactic polypropylene has made investigation into its morphological structure possible. Recent studies have indicated that the morphological structure of syndiotactic polypropylene involves an orthorhombic unit cell containing helices wound in different directions or a zig-zag chain conformation, depending on the crystallization conditions. Lamellae formed by isothermal crystallization show radial growth. In thin films, high isothermal crystallization temperatures (100–145°C; 212–293°F) resulted in rectangular single lamellar crystals containing transverse cracks. As the crystallization temperature was reduced, growth became more spherulitic, with spherulite morphology prevailing at 100°C (212°C). [770, 732, 784]

The increased chain flexibility of syndiotactic polypropylene, compared to the isotactic form, allows it to move around more easily in the melt phase of processing. Recent experiments indicate that this increased flexibility leads to a significantly higher number of molecular entanglements in the melt, which may contribute to its improved UV and gamma radiation resistance, increased elasticity, and tear strength in cast films. Molecular entanglements occur above a critical molecular weight, providing resistance to flow and inhibition of crystal growth. [777]

2.2.5 Mesomorphic polypropylene

The mesomorphic or smectic form of polypropylene is a noncrystalline phase, intermediate in order between crystalline and amorphous forms. Early experiments indicated that this form may be a paracrystalline phase resulting from deformed or distorted lattice structures. Examples of lattice defects include atoms forced out of normal lattice or unit cell positions due to surrounding amorphous material, changes in polymer chain folding, the presence of atoms of foreign material in the lattice, and screw dislocations that disrupt the spherulite structure by initiating lamellar growth in an irregular location. Polymer chains have been shown to form helical structures, but the unit cell and lamellar structures have not yet been well resolved. Experiments indicate a lack of lamellar order in addition to a low density and small size of ordered structures. These characteristics result in high clarity, useful in quenched film applications. [770, 772, 769]

2.2.6 Amorphous polypropylene

In atactic polypropylene, with its random molecular structure, molecules cannot crystallize in an ordered form, and a polymer with low crystallinity is formed. Low crystallinity polymers consist of ordered, crystalline regions surrounded by disordered, spaghetti-like amorphous material with entangled polymer chains. [772, 769] Amorphous polypropylene has no defined melting point. It behaves like an elastic and plastic material and is tough and flexible. It is used for hot melts and pressure sensitive adhesives, films for sound insulation, and for modifying rubber, polyethylenes, bitumen, and asphalt. [747]

2.3 Effect of morphology on characteristics of polypropylene

Due to the ordered crystal structure, semicrystalline polymers generally have high strength and are more chemically resistant than amorphous polymers. Semicrystalline materials are more opaque and can be used at higher temperatures, while amorphous materials are generally more transparent and have greater toughness and ductility. [772]

2.3.1 Melting point

The crystalline structure of a solid semicrystalline polymer disappears at the melting point, T_m , when the material undergoes a phase change from solid to liquid. At the melting point, physical properties of the material, such as density, refractive index, heat capacity, and transparency, change abruptly as the material becomes a viscous liquid. Melting points are commonly measured using differential scanning calorimetry (DSC). [769, 772]

The melting point of a polymer varies with the amount of crystallinity. A perfectly isotactic polypropylene resin has a theoretical melting point of about 171°C (340°F); melting points of commercial isotactic resins can range from 160–166°C

(320–331°F) due to atactic material and noncrystalline regions. Melting points decrease dramatically with lower crystallinity; a syndiotactic polypropylene resin with a crystallinity of 30% melts at approximately 130°C (266°F). [693]

Polymers generally melt over a narrow temperature range rather than at a distinct point. In a resin with a particular crystallinity, variations in chain lengths produce lamellae of varying thicknesses, which melt at slightly different temperatures. The melting point given for a polymer is generally the temperature at the highest point of the peak on a DSC scan (Figure 2.4) [770, 730]

The high melting point of polypropylene provides resistance to softening at elevated temperatures. Standard grades of polypropylene can withstand continuous service temperatures of over 107°C (225°F) and over 121°C (250°F) for short periods of time. The superior heat resistance of polypropylene makes it suitable for sterilization by autoclaving at temperatures of over 121°C (250°F) and for hot-fill applications. Heat resistance is lowered for resins with lower melting temperatures. [780, 696, 642, 693]

2.3.2 Glass transition

Amorphous regions of the polypropylene resin undergo a glass transition (T_g) at a temperature between –35 and 26°C (–31 and 79°F), depending on the measurement method, heating rate, thermal history, and microstructure. The glass transition temperature is related to the amount of free volume in a polymer. Molecules and segments of polymer chains above the glass transition temperature vibrate and move in noncrystalline polymer regions. Motions include diffusion, rotation about bond axes, and translation under mechanical stress. At the glass transition temperature, free volume is restricted, and only low amplitude vibrations can occur. This movement continues down to absolute zero, at which point all movement ceases. Resins with lower molecular weight generally have lower glass transition temperatures due to increased free volume at the ends of the polymer chain and lower degrees of chain entanglement. [772, 693]

Normal use temperatures of polypropylene are generally between the glass transition and melting temperatures, so that strength and stiffness from the crystalline region are combined with toughness of the amorphous “tie points”. The low temperature ($\leq 5^\circ\text{C}$; 40°F) brittleness of polypropylene is

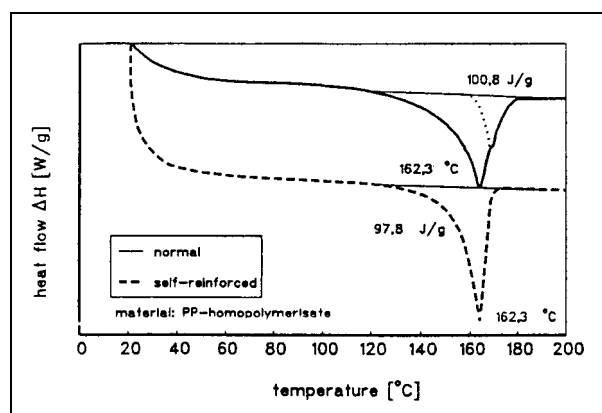


Figure 2.4 A differential scanning calorimetry (DSC) melting scan of injection molded polypropylene. In DSC, a polypropylene sample is heated, along with a reference material, and the energy required to maintain both materials at the same temperature is monitored as the surrounding temperature is increased. Heat is absorbed by polypropylene as it melts, resulting in an endothermic peak; the melting temperature given in the literature is the highest point of the peak. DSC scans of polypropylene frequently show more than one peak, due to polymorphism or crystalline changes that occur during the heating cycle. Bottom scan is normally processed polypropylene. Top scan is polypropylene with an oriented crystallization, produced with a high injection rate and pressure. A small high temperature shoulder indicates the presence of more than one morphological form. Heating rate was 10 K/min (10°C/min; 18°F/min). [789]

due to its relatively high glass transition temperature; as the temperature drops, approaching the glass transition temperature, the resin becomes increasingly brittle, and impact resistance becomes negligible. [693]

2.3.3 Mechanical properties

Mechanical properties of polypropylene are strongly dependent on its crystallinity. Increasing crystallinity increases stiffness, yield stress, and flexural strength but decreases toughness and impact strength. The secant flexural modulus at 1 % displacement can range from 2067–2412 MPa (300,000–350,000 psi) for polypropylene with ultra-high crystallinity but decreases to 1378–1654 MPa (200,000–240,000 psi) for general purpose polypropylene of lower crystallinity. In experiments with α -form, isotactic polypropylene, increasing crystallinity increased the growth of cracks and decreased fracture toughness. [693, 785]

Spherulite size affects the strength and ductility of the resin. In studies of fatigue strength, different crystallization temperatures were used to produce spherulites of different sizes (37, 54, and 61 μm); higher crystallization temperatures produced larger diameter spherulites. In fatigue fracture tests investigating the effects of a sharp initial crack, the resin with smaller spherulites exhibited more ductile behavior, with more damage ahead of the crack tip and crazing in the surrounding region. Larger spherulite sizes resulted in more brittle behavior, with less material damage. Slow crack growth changed to unstable crack growth at a critical crack length; this length decreased as spherulite size increased. [778]

In investigations of the fracture behavior of nucleated and non-nucleated isotactic polypropylene using the J-integral method, fracture toughness decreased with increasing crystallinity, for both nucleated and non-nucleated resins. An increase in spherulite size from 25 to 100 μm decreased fracture toughness and increased brittleness in non-nucleated polypropylene. Nucleated polypropylene, with a spherulite diameter of 2 μm , exhibited increased crystallinity and brittleness, and cracks grew faster after initiation, leading to early failure. It was proposed that this brittleness was due to the higher crystallization temperature of nucleated polypropylene. Higher crystallization temperatures increase the lamellar thicknesses and decrease tie-molecule concentrations of amorphous regions; since tie molecules provide mechanical continuity between spherulites,

lower tie molecule concentrations would make the amorphous regions of the polymer more susceptible to crack propagation. [785]

2.3.4 Haze

Transparency in semicrystalline polymers is directly related to the crystallinity. Spherulites are much larger than the wavelength of visible light (0.4–0.7 μm), and the refractive index of crystalline regions is higher than that of amorphous regions. As light rays pass from amorphous to crystalline regions, they encounter the large spherulites, resulting in light scattering; as a result, transparency is lower, and haze is produced. Due to their noncrystalline structure, amorphous materials have lower levels of haze than semicrystalline materials, and a decrease in crystallinity in a semicrystalline polymer enhances the clarity. Excessive reductions in crystallinity can result in unacceptable reductions in strength, stiffness, and resistance to softening, so a compromise must be reached that is appropriate for the application. [693, 780, 786, 774]

Nucleating agents such as dibenzylidene sorbitols reduce spherulite size to below a level that scatters visible light, resulting in a dramatic reduction in haze. Spherulite size distribution is also reduced. A higher concentration of nucleating agent can result in greater clarity. Clarity can be optimized by using a resin with low crystallinity with a nucleating agent added and by rapidly cooling the molten polymer to accelerate the crystallization rate. [693, 786]

2.3.5 Sterilization

Polypropylene resins with lower crystallinity exhibit greater resistance to embrittlement resulting from gamma radiation sterilization. Exposure to gamma radiation increases the susceptibility of the material to oxidation. Free radicals and ions, highly reactive chemical species containing free (nonbonded) electrons, are created and are then trapped in the crystalline structure of the polymer. These free radicals and ions promote covalent bond disruptions in the main polymer chain or in pendant methyl groups. The resulting chain scission and/or crosslinking of adjacent polymer chains increases the brittleness of the material. [55, 799, 798]

Radiation resistance is associated with the amount of free volume in the polymer structure, which allows greater mobility of the polymer chains. Amorphous or smectic phases have lower densities

and greater free volumes than crystalline regions; resins with increased amounts of these less ordered phases exhibit increased radiation resistance. Polymers with low isotacticity combined with careful selection of additives are effective in producing radiation-resistant materials. [780, 67, 699]

2.4 Orientation

When a polymer crystallizes in the absence of external forces, the polymer chains are arranged randomly, in no preferred direction. If the polymer is subjected to an external stress (such as flexing) immediately after crystallization (while it still retains heat), the polymer chains align in the direction of the external stress. [769, 420] Orientation is used in the production of films, fibers, blow molded bottles, and living hinges, and some orientation occurs during the injection molding process.

2.4.1 Fibers and films

Orientation can be uniaxial, in which the material is stretched or drawn in one direction (machine direction), or biaxial, in which the material is stretched in two directions (machine direction and cross or transverse direction). Uniaxial orientation is used for films and fibers, and balanced biaxial orientation, in which the machine and transverse direction draw ratios are equal, is used in films and blow molding. Stretching is usually performed at a temperature slightly below the melting temperature (120–160°C; 248–320°F for polypropylene), when crystals are partially melted, and the desired shape is maintained during cooling. [642, 774, 772]

When unoriented fibers are stretched or drawn, the fiber does not become gradually thinner; instead, it suddenly becomes thinner at one point, a process called “necking down”. In necking, the original material becomes oriented locally and is separated from unoriented material by a relatively sharp boundary. Continued stretching results in increased length of the drawn portion at the expense of the undrawn portion of the fiber. Diameters of both drawn and undrawn portions do not change significantly during the stretching process. [769, 889] During the orientation process, spherulites break apart as blocks of lamellae slide out and rotate, and molecular chains slide past each other to become oriented in the same direction. Microcracks can form between crystallites, and small crystallites stack into long, thin fibrils. Oriented lamellae are connected by tie molecules

in amorphous regions. The stereoregular structure of polypropylene allows the oriented polymer chains to fit together well, so that the alignment is maintained only by van der Waals forces between different polymer molecules. [768, 769, 774]

Shrinkage of the oriented material can occur over time at room temperature, and if heated to a temperature approaching the orientation temperature, shrinkage becomes significant. To reduce shrinkage at room temperature and to raise the temperature at which significant shrinkage occurs, the material is annealed by heating to a temperature just below the melting temperature; the amorphous tie regions relax, allowing movement of some polymer chains in this region into crystalline structures. [772, 774]

2.4.2 Effect of orientation on characteristics of fibers and films

The alignment of polymer chains in oriented materials makes formation of a crystalline structure easier, resulting in increased crystallinity. Stiffness and strength increases when the applied stress is in the orientation direction and decreases compared to unoriented material when the applied stress is perpendicular to the orientation direction. Strength results from the covalent bonds between carbon atoms of the polypropylene chain; orientation increases the number of polypropylene chains aligned in the orientation direction, increasing the number of covalent bonds. As a result, a smaller amount of material can carry the same applied load. [774, 772]

Permeability in biaxially oriented polypropylene film is reduced dramatically due to the increased crystallinity; molecules cannot easily diffuse through the crystalline matrix. Permeability to moisture is decreased, and oil and grease resistance is increased. The increase in crystallinity also increases its dielectric strength; biaxially oriented films can withstand three times the voltage of unoriented film before dielectric breakdown occurs. The nonwettability and stain resistance of fibers makes them useful in applications such as marine rope, upholstery, and carpeting. The wicking action of polypropylene makes it useful in sportswear; moisture is not absorbed but passes through to the other side by capillary action of fibers with large surface areas, and the material remains dry. [642, 783, 773, 705]

Optical properties are improved in biaxially oriented film. In unoriented films, interfaces between crystalline and amorphous regions, which

Table 2.1 Effect of Increasing Biaxial Orientation on Properties of Polypropylene

Property	With Increasing Orientation
Tensile Strength at Yield	Increases
Modulus	Increases
Drop Impact Strength	Increases
Cold Temperature Impact Strength	Increases
Permeability	Decreases
Haze	Decreases
Gloss	Increases
Shrinkage	Increases

refract light to produce haze, are distributed in all directions. In oriented film, the alignment of lamellae results in fewer interfaces in the plane of the film. Less light is refracted, reducing haze and increasing the clarity. In addition, the smoother spherulitic surfaces of oriented film scatter less reflected light, so that gloss is increased. [881, 774]

Shrinkage is higher in oriented materials, due to relaxation of the aligned structure back to a more random morphology. If not annealed, films exposed to temperatures close to the orientation temperature will shrink to a structure similar to that of the unoriented material, a property that is exploited in heat shrinkable films. [642, 881]

General effects of biaxial orientation on polypropylene are listed in Table 2.1. [695]

2.4.3 Injection molding

Orientation in injection molding arises from shear stress during flow and cooling of the molten polymer as the mold is filled. Orientation is produced in the direction of polymer flow. During mold filling, polymer chains are stretched and uncoiled due to shear and elongational forces; chains then relax slightly during the cooling period before crystallization occurs. After crystallization, the remaining orientation is frozen in. The time and extent of relaxation is dependent on properties of the particular resin, such as molecular weight and molecular weight distribution, the difference in temperature between the polymer melt and the mold walls, and processing conditions. [770]

The flow and cooling process produces a skin-core morphology in injection molded parts. Depending on the flow pattern of the melt, different morphologies can be observed between the skin, at the surface of the mold where cooling is rapid, and

the core, in the center of the mold where cooling is slower. In some cases, a continuous decrease in orientation has been observed from the skin to the core layers. The skin layer is highly oriented due to shear forces during flow and rapid cooling. Shish-kebab structures (Figure 2.5) are produced, with lamellae oriented in the flow direction, and some β -form crystallites form due to the high melt strain in this region. [734] In the core region, there is less melt strain, in addition to slower cooling, so that any orientation that occurs has time to relax back to an unoriented morphology. As a result, a spherulitic structure is produced, with little or no orientation. A continuous increase in unoriented spherulitic morphology is observed from the skin to the core. [734, 770]

Another type of morphology often observed exhibits three layers: a skin layer, a core layer, and a layer of maximum orientation between the skin and core. The skin layer has been attributed to elongational forces arising from fountain flow at the front and displays either no orientation or a limited amount of orientation. In fountain flow, the melt front stretches and balloons out to cover the mold wall. Cooling is rapid, and the melt freezes when it meets the mold walls. The frozen layer along the walls produces a non-uniform velocity gradient in the transverse direction of the mold; melt in the center, with the highest velocity, then flows out to the mold walls and freezes. [526, 787, 774]

Maximum orientation and some β -form spherulites occur in the shear zone. The polymer melt in this region is attached to the frozen skin layer but is still moving with the melt front, producing high shear strain. In the center core region, low shear strain results in low orientation. [787, 734, 772]

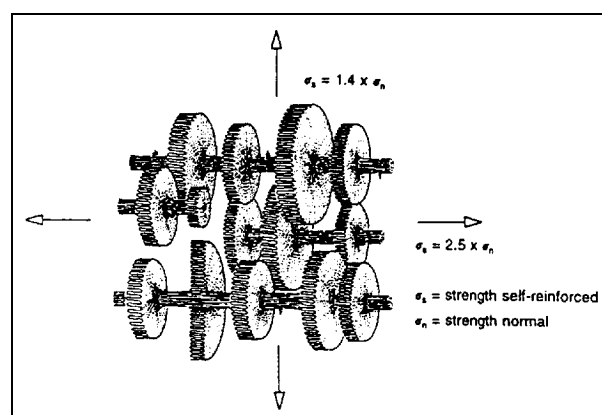


Figure 2.5 Drawing of a shish-kebab structure in polypropylene. Shear forces during melt flow into the mold cavity produce deformation of spherulitic structures, and lamellae become aligned in the flow direction. [789]

Crystallinity increases from the skin layer to the core, due to a higher cooling rate at the surface, and formation of β -form crystallites decreases. Spherulite size increases from the skin to the core region — the higher cooling rate at the mold walls produces faster nucleation and smaller spherulites. [770, 734]

Processing parameters and resin properties can affect morphology. In experimental studies, melt temperature was the most important parameter affecting spherulite size and skin layer thickness. Increasing melt temperatures resulted in decreased skin layer thicknesses due to chain relaxation from increased cooling times, and spherulite diameter decreased due to slower nucleation rates. Skin layer thickness also decreased with increasing mold temperature, due to decreased cooling rates, but increased slightly with increases in holding time. Skin layer thickness also increased with increasing polymer molecular weight, due to a longer relaxation time for longer polymer chains. Spherulite diameter increased with increasing melt temperatures due to slower nucleation rates. [734, 770]

2.4.4 Effect of orientation on characteristics of injection molded parts

Orientation imparts a directionality or anisotropy on the properties of injection molded parts. Mechanical properties depend on the direction of the applied stress; oriented materials are generally stronger than unoriented materials when stress is applied in the flow direction, but weaker with stress applied in the transverse direction.

Tensile strength is high in the flow direction, due to the strength of covalent bonds between carbon atoms along the polymer chain, but low in the normal or transverse direction, due to the weak intermolecular forces between polymer chains. With a completely oriented, extended polypropylene chain, ultimate strength in the flow direction could be as high as 16 GPa (2,300,000), with a modulus of 50 GPa (7,200,000 psi); this is not achieved in practice due to the spherulitic crystal structure. Impact strength follows the same pattern as tensile strength. [772, 789]. Tensile modulus, yield strength, and flexural modulus all increase in the flow direction as orientation increases. Softening temperatures are higher in the skin layers relative to the core layers. [770]

Orientation induces residual stress in injection molded parts, which can result in decreased impact resistance and warpage. Stress relaxation can re-

sult in shrinkage; when exposed to elevated temperatures after demolding, an oriented material will shrink more in the direction of orientation than in the transverse direction. Shrinkage has been correlated with the area fraction of the skin layer. [770, 772]

Orientation influences thermal, chemical and electrical properties of injection molded parts. The thermal conductivity increases in the flow direction, while the coefficient of linear thermal expansion increases in the transverse direction and decreases in the flow direction. The electrical dissipation factor decreases in the orientation direction, and permeability increases in the transverse direction. [772]

Orientation affects the radiation resistance of polypropylene. In experiments that determined the break-angles of plaques after gamma irradiation, samples tested in the transverse direction showed dramatic losses in ductility, while samples tested in the orientation direction generally retained ductility up to 1000 hours after sterilization. Flexural moduli of identical samples not irradiated showed only a small orientation effect, with moduli measured in the flow direction slightly higher. [700]

2.4.5 Living hinges

The high strength in the direction of orientation is used in the production of integral or living hinges — molded-in, one-piece hinges that allow part opening and closing without use of a mechanical hinge. Polypropylene living hinges can be flexed a million times before failure and are used in applications such as videocassette cases and fishing tackle boxes. [420, 773]

The design of a polypropylene living hinge includes a thin section (hinge web) connecting two heavier sections (Figure 2.6). A recess is located in the upper portion of the thin region, to prevent any cracking that could result in hinge breakage. An arc below the thin section allows for flexing and orientation. The polymer chains are initially unoriented after molding; the hinge is flexed immediately after molding, while the part temperature is still high, to induce orientation. The hinge web is stretched during the initial flexing, and polymer chains become aligned perpendicular to the hinge. As with any orientation process, strength in the orientation direction is greatly increased due to carbon-carbon covalent bonds, resulting in a tough, fatigue-resistant hinge. [420, 690, 773]

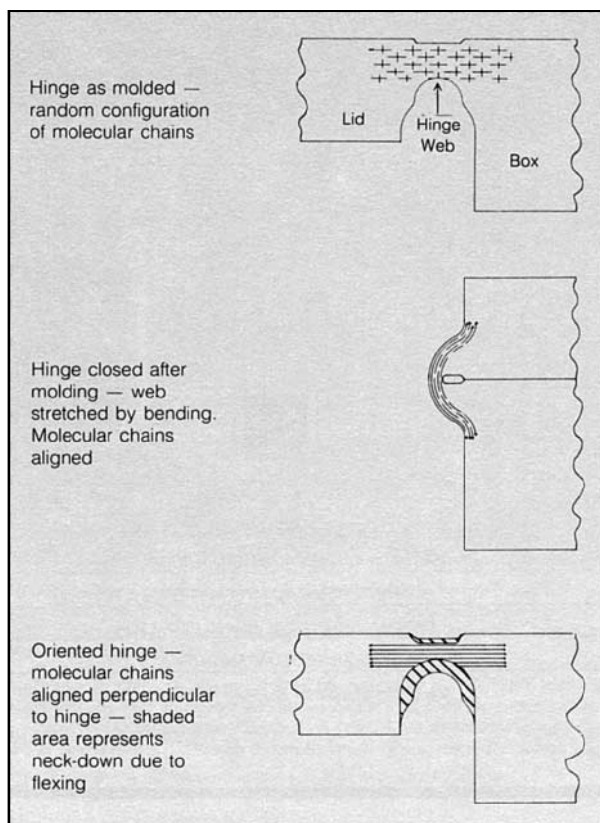


Figure 2.6 Formation of a living hinge, shown for a fishing tackle box. Top, hinge immediately after molding. A thin section (hinge web) connects two larger sections (lid and box). A recess at the top of the hinge web prevents cracking, and an arc below allows for flexing and orientation. Polymer chains are unoriented. Middle, hinge is closed after molding, while the part is still warm, to induce orientation. Bottom, the oriented hinge. Polymer chains are aligned perpendicular to the hinge, providing high fatigue strength. Neck-down occurs in the shaded regions due to flexing. [420]

2.5 Commercial Forms of Polypropylene

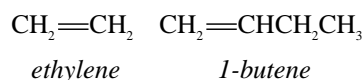
Polypropylene is produced commercially in different forms, depending on the properties desired. Polypropylene homopolymer contains only propylene monomer in the polymer chain. Homopolymer provides stiffness and toughness but exhibits low impact strength at low temperatures, and clarity is too low for some applications. Propylene copolymers contain one or more different types of monomers in the polymer chain. Random copolymers are used in applications requiring higher clarity or a lower melting point, and impact copolymers are used in automotive and other applications that require high impact resistance at low temperatures. Thermoplastic olefins and thermoplastic vulcanizates provide elastomeric properties for automotive, medical, and other applications.

2.5.1 Homopolymers

The chemistry and morphology of polypropylene homopolymer have been described in the preceding sections. The primary application of homopolymers is in the extrusion of fibers and filaments for cordage, webs, carpet backing and face yarns, upholstery fabrics, apparel, filters, geotextiles, disposable diapers, medical fabrics, fabric for automobile interiors, bags, and strapping tape. Oriented and unoriented films are also extruded for pressure-sensitive tapes, electrical applications, shrink film, and packaging for retortable pouches. Sheets greater than 250 μm (10 mil) in thickness are used for counter tops and tank liners; thinner sheets are thermoformed into packaging containers. Injection molded homopolymers are used in automobile parts, appliances, housewares, packaging containers, trigger sprayers, furniture, and toys. [795, 788]

2.5.2 Random copolymers

Random copolymers are produced by adding the comonomer, ethylene or, less commonly, 1-butene or 1-hexene, to the reactor during the polymerization reaction: [691]



The comonomer substitutes for propylene in the growing polymer chain. Insertions are randomly or statistically distributed along the chain and can consist of single monomers, as shown for ethylene in Figure 2.7, or multiple monomers (two or more sequential ethylene molecules along the polymer chain). Random copolymers generally contain 1–7 wt.% ethylene, with 75% single and 25% multiple insertions. In practice, depending on the catalyst, polymerization conditions, and the reactivity of the comonomer compared to propylene, random copolymers can become somewhat blocky, with some regions of the polymer chain containing only polypropylene units and other regions containing only comonomer. [693, 795, 691]

The structure of random copolymers is similar to isotactic polypropylene, but the regular, repeating arrangement of atoms is randomly disrupted by the presence of comonomer units. The effect is similar to that of increasing atacticity. Crystallinity

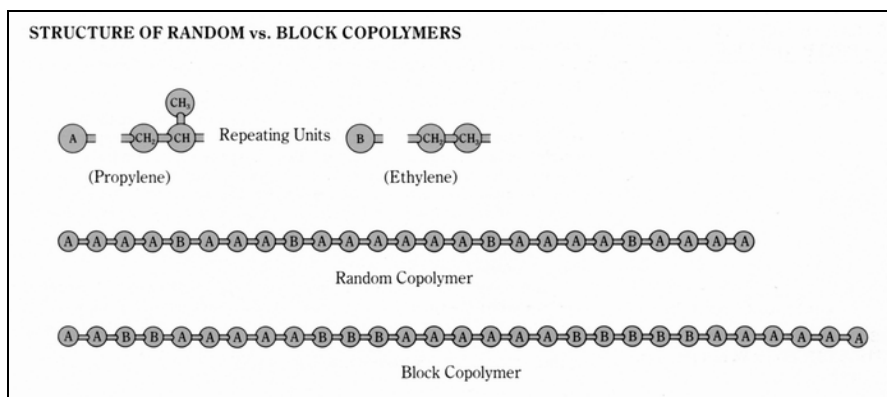


Figure 2.7 Random and impact copolymers, shown using ethylene as the copolymer. In random copolymers, ethylene is added to the reactor during the polymerization reaction. Ethylene units insert randomly along the polypropylene chain, disrupting the regular, repeating structure and reducing the crystallinity compared to isotactic polypropylene. Random copolymers can contain up to 7% ethylene. In impact or block copolymers, ethylene is added during propylene polymerization or blended in afterwards. The amount of ethylene added can be as high as 25%. The added ethylene forms a dispersion of particles in the semicrystalline polypropylene matrix, providing elastomeric properties to the resin, such as high impact strength at low temperatures. [642]

is reduced, and mobility of the polymer chain is increased due to less steric interaction of the pendant methyl groups of polypropylene. [693]

2.5.2.1 Characteristics of random copolymers

Due to the lower crystallinity, random copolymers have lower melting points and specific gravity than homopolymers. Melting points can be as low as 120°C (250°F) with 7% ethylene comonomer inserted in single units. Multiple ethylene insertions do not contribute significantly to changes in melting point. The specific gravity of random copolymer is slightly lower than homopolymer, ranging from 0.89–0.90. Lower melting points result in lower heat distortion (63–96°C; 145–205°F at 0.45 MPa; 66 psi) and softening temperatures (softening temperatures in polypropylene range from 140–155°C; 284–311°F), and lower heat sealing temperatures make random copolymers useful in heat-sealable films. [693, 691, 869]

Glass transition temperatures of random copolymers are generally lower than homopolymers, depending on the type, amount, and distribution of copolymer. Reduced crystallinity and increased amounts of amorphous material, in addition to lower glass transition temperatures, result in somewhat higher impact strength in random copolymers. Gardner impact strength of a random copolymer with 3% ethylene is about 28 J (250 in.-lb.), while that of a typical homopolymer is about 11 J (100 in.-lb.). Impact resistance at lower temperatures is increased in random copolymers; moderate impact

strength is retained at temperatures as low as 0°C (32°F), with limited utility to –20°C (–4°F). [693, 696]

Reduced crystallinity also results in decreased stiffness and hardness and increased softness and flexibility. Ultimate tensile strength of high-crystallinity homopolymers can exceed 34 MPa (5000 psi); in random copolymers containing 3–4% ethylene, strength drops to about 14 MPa (2000 psi). General purpose homopolymers exhibit secant flexural moduli (at 1% strain) ranging from about 1000–1600 MPa (150,000–240,000 psi); values are reduced to 480–1000 MPa (70,000–150,000 psi) in random

copolymers. At comparable values of melt flow index, random copolymers are softer than homopolymers; hardness increases at lower temperatures. [693, 788, 695, 795]

Clarity increases dramatically in random copolymers; typical haze values of 55–70% in homopolymers are cut in half in a random copolymer with 5% ethylene. Copolymer-induced irregularities in the polymer chain result in crystalline regions with a lower index of refraction. Because the difference in refractive index between amorphous and crystalline regions is not as great, less light is scattered or refracted as it passes from amorphous to crystalline regions, resulting in lower haze. High clarity, which can be further enhanced by the use of additives, makes random copolymers useful in film, blow molded bottles, and food storage containers. [693, 774, 797]

2.5.2.2 Sterilization of random copolymers

The presence of copolymer in a polypropylene resin provides stability against gamma radiation, due to the lower crystallinity and greater free volume. Random copolymers containing ethylene are commonly used, with appropriate additives, for radiation-resistant formulations. [67, 693] In experiments with random copolymers containing up to 2.8% ethylene and standard additives for medical device formulations (hindered amine light stabilizers and nucleating clarifiers), samples were exposed to 0–100 kGy of cobalt–60 gamma radiation and aged at 60°C (140°F) for 21 days; samples with increased

ethylene content showed improvement in Gardner impact strength, tensile elongation at break, and deflection at peak flexural load. [699]

Lower heat distortion temperatures of random copolymers compared to homopolymers provide lower resistance to autoclave sterilization. Unstressed radiation-resistant random copolymers (with 3% ethylene) can sometimes withstand autoclaving at 120°C (250°F) for 15–60 minutes; however, parts autoclaved when significantly stressed can deform during autoclave treatment. Stress can be due to pressure, a vacuum, the weight of liquid contents, or an elastic seal; a disposable hypodermic syringe is highly stressed due to pressure exerted on the syringe wall by the plunger tip. Higher crystallinity in the random copolymer is necessary to withstand stress during autoclave treatment. [693, 780]

2.5.2.3 *Applications of random copolymers*

Random copolymers are primarily used in film, blow molding, and injection molding applications that require high clarity, good impact strength at low temperatures, some stiffness, and moisture barrier properties. Blow molding applications include hot-filled and multilayer barrier bottles and refrigerated products for medical and food packaging. Rigid and semi-rigid packaging, video cassette cases, toys, storage trays, and reusable food containers are injection molded. Film applications include flexible packaging and consumer products. Unoriented heat-seal films are used for packaging in food and clothing and to provide strength and barrier layers in disposable diapers. Oriented films provide high clarity, gloss, and strength for shrink-wrap applications in toys, games, cigarettes, and foods. Coextruded oriented films with a high ethylene content (3–7%) are used as one- or two-sided heat sealable layers in food packaging, especially of snack foods. The lower melting point (<132°C; 270°F) of random copolymers is cost effective due to the increased speed of packaging lines, and the resin can be recycled with no significant loss of strength or clarity. [691, 788, 794]

2.5.3 **Impact copolymers**

Impact copolymers are formed by the addition of ethylene-propylene rubber (EPR), ethylene-propylene-diene monomer (EPDM), polyethylene, or plastomers to homopolymers or random copolymers. Copolymer levels in impact copolymers range from 5–25%.

Plastomers are very low density (<0.880 g/cc) copolymers of ethylene and an olefin (such as ethylene-butene) produced using metallocene catalysts. Due to the single polymerization site on metallocene catalysts, comonomer can be inserted uniformly, producing a homogeneous copolymer with both elastomeric and plastic characteristics. They have a narrow molecular weight distribution and more long-chain branching than EPDM or EP rubbers. [803, 758, 693, 182, 695, 642, 794, 798, 795, 804, 814]

Impact copolymers containing ethylene-propylene rubber are made using cascaded reactors. Homopolymer formed in the first reactor is transferred to a second reactor, where copolymerization with ethylene is performed to produce EPR within the polypropylene matrix. EPDM, ethylene-propylene, or polyethylene can also be compounded into post-reactor homopolymer to form a super high impact blend. Both compounded and reactor-produced material can be tailored to suit a specific application; compounded resin is not as susceptible to surface blushing, a problem with reactor-produced copolymers. [693, 182, 695, 642, 794, 798, 795]

Due to the high levels of copolymer used in impact copolymers, the copolymer is not miscible in homopolymer; it usually forms an amorphous elastomeric or rubber phase that is evenly distributed throughout the polypropylene crystalline matrix. The phase separation results in copolymer nodules distributed throughout the semicrystalline homopolymer matrix. The elastomeric nodules provide impact resistance by acting as small bumpers, absorbing energy that results in local deformation instead of allowing cracks to propagate through the material. [795, 695]

The specific morphology and crystallinity of the impact copolymer is determined by the chemical composition and quantity of the elastomeric phase and by the molecular weights and relative viscosities of the homopolymer and the elastomeric phase. The separate morphology of the elastomer phase is affected by melt processing, compounding, and the shear and deformation forces that occur in injection molding. [795]

Orientation produced during injection molding can impose a directionality on toughness-related properties, so that craze propagation parallel to the elastomeric phase nodules may not be inhibited. In experiments with polypropylene impact-modified with ethylene-propylene rubber, physical properties varied significantly with molding conditions

and sample location. Samples with a broader molecular weight distribution exhibited higher variation in physical properties than those with a lower MWD. Flexural moduli and notched Izod impact strength were higher in samples in the direction of flow into the mold cavity than in the cross-flow direction; stiffness was highest near the gate. Increasing melt temperatures resulted in decreased flexural moduli, due to lower orientation, and lower impact strength. Increasing mold temperatures resulted in slightly higher flexural moduli in samples regardless of mold location, probably due to increased crystallinity; mold shrinkage was also slightly higher. Shrinkage was most significantly decreased with increasing mold cavity pressure; increasing injection speed caused a moderate increase in mold shrinkage. [770, 156, 802]

Blush formation can be reduced by introducing a small amount of crystalline material in the

generally amorphous elastomeric phase. Blushing or stress whitening occurs when a deformation in the part produces a microcrack that refracts light; a white-colored area forms along the microcrack. The amorphous elastomer phase contracts much less during melt cooling than the semicrystalline homopolymer matrix; increasing the crystallinity of the elastomeric phase, usually by adding polyethylene during compounding, makes volume contractions of the two phases more similar. As a result, lower residual stress is produced during melt cooling and greater deformation can occur without blush formation. Stress whitening in toys and furniture has been reduced by the use of 0.88 density butene plastomers [759, 815, 882, 158]

2.5.3.1 Characteristics of impact copolymers

Impact or block copolymers are primarily used when increased impact resistance or toughness is required, especially at low temperatures. Impact resistance is dependent on the type, amount, and morphology of the elastomeric phase, while stiffness is determined by the polypropylene matrix. Notched Izod impact strengths of impact copolymers, 2.0–20 J (1.5–15 ft.-lb./in.) are higher than those of homopolymers, 0.7–1.4 J (0.5–1.0 ft.-lb./in.), and homopolymers become brittle at temperatures $\leq 5^{\circ}\text{C}$ (41°F), with a dramatic loss of impact strength. [795, 691] The Gardner impact strength at -30°C (-22°F), a measure of low temperature toughness, ranges from 1.1 to 2.8 J (10–25 in.-lb.) in homopolymers but increases to 5.5–40 J (50–350 in.-lb.) in impact copolymers. [696, 795, 691, 758]

The higher impact strength of impact copolymer also results in loss of stiffness or rigidity. As the percentage of copolymer is increased in an impact copolymer resin, toughness increases and stiffness decreases, and heat distortion temperature decreases. The relationship between toughness, represented by Gardner impact strength, and stiffness, according to the flexural modulus, is shown in Figure 2.8. Impact copolymers containing fillers such as glass fiber, mica, talc, and calcium carbonate can generally withstand higher temperatures without significant distortion. Depending on the properties required for the particular application, trade-offs must be made among impact strength, stiffness, and heat distortion temperatures. [795, 696]

In experimental studies, a clear, autoclavable polypropylene formulation with resistance to radiation was produced using a nucleated homopolymer stabilized with hindered amine light sta-

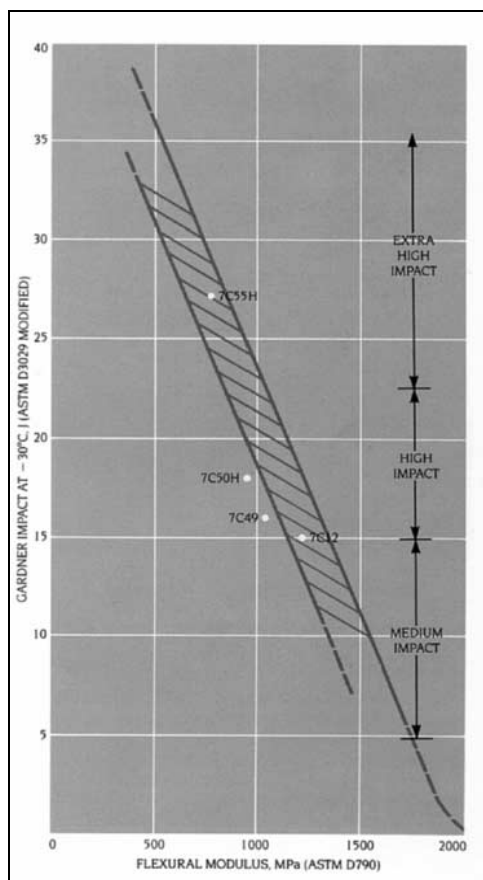


Figure 2.8 The relationship between impact strength and flexural modulus of impact copolymers at -30°C (-22°F). As impact strength or toughness, measured by the Gardner falling weight impact test, increases, the stiffness of the resin, measured by the flexural modulus, decreases, so that the proper balance of properties must be selected for a particular application. Impact strength increases as the amount of copolymer in an impact copolymer formulation increases. [696]

bilizers and 7.5–10% of an ethylene plastomer. The plastomer also improved the whiteness of the blends before and after irradiation. [780]

2.5.3.2 Applications of impact copolymers

Impact copolymers are primarily used in injection molding parts for appliances, housewares, luggage, outdoor furniture, and automotive applications. Other applications include extruded sheeting and substitutions of super impact grades for engineering thermoplastics such as ABS. Extruded sheets can be thermoformed into large, thick parts such as fender and trunk liners for automotive applications or into small, odd-shaped parts such as food containers for freezer-to-microwave use. Melt flow rates of extrusion grades range from <1–4 g/10 min. Medium-impact polypropylene, generally with a higher melt flow rate, is used in interior automobile parts, while high impact grades are used for battery cases and exterior parts of cars. [691, 795, 182, 788]

2.5.4 Random block copolymers

Random block copolymers are recently developed copolymers in which particles of ethylene propylene rubber are distributed through a random copolymer polypropylene matrix. Random block copolymers display high stiffness and toughness, and the added softness of the random copolymer matrix results in less stress whitening than in impact copolymers. [939]

2.5.5 Thermoplastic olefins

Thermoplastic olefins (TPOs) are a blend of two polymer systems, with usually polypropylene or polyvinyl chloride as the crystalline matrix and ethylene propylene rubber, ethylene propylene diene monomer, or metallocene-produced plastomers (i.e. ethylene-octene, ethylene-butene) as the elastomeric phase. The distinction between impact copolymers and thermoplastic olefins is not well defined; usually elastomer levels over about 20% are referred to as thermoplastic olefins. [805, 814]

TPOs can be made by blending EPDM or EP rubber with polypropylene in a batch mixer or by forming the EP rubber phase during propylene polymerization in the reactor. Reactor production is more cost-effective, resulting in up to 10–15% cost savings over traditional compounding due to continuous operations. Reactor-made rubber phases have finer particle sizes that are more uniformly distributed in the polypropylene matrix; however, properties cannot be tailored for specific applications. [814]

The morphology of thermoplastic olefins is similar to that of impact copolymers, with dispersed phase particles distributed over a polypropylene crystalline matrix. At high elastomer levels, dispersed and matrix phases are reversed — polypropylene dispersed in an elastomeric matrix. Homopolymer, random copolymer, or impact copolymer can be used as the base resin. [806]

Optimum particle dispersion and cold temperature impact resistance are obtained with particle sizes of $\leq 1\mu\text{m}$. Elastomer and polypropylene phases are more compatible, producing finer particles, when the viscosity differences between the two phases are lower (elastomer / polypropylene viscosity ratio is minimized). The viscosity ratio increases with decreasing polypropylene molecular weight (increasing melt flow rate). In experiments, the viscosity ratio of ethylene-butene plastomers decreased in high melt flow rate resins (35 g/10 min.) as the shear rate during compounding increased, suggesting that high shear is required for optimal dispersion in high melt flow rate resins. Viscosity ratios of resins with low melt flow rates (1.7–20.0 g/10 min.) were almost independent of shear rate. [816, 801]

In other experiments, metallocene-based plastomers produced finer particle dispersions than the traditional ethylene-propylene rubber used in thermoplastic olefins (Figure 2.9). The higher flow rates of the plastomers (compared to ethylene-pro-

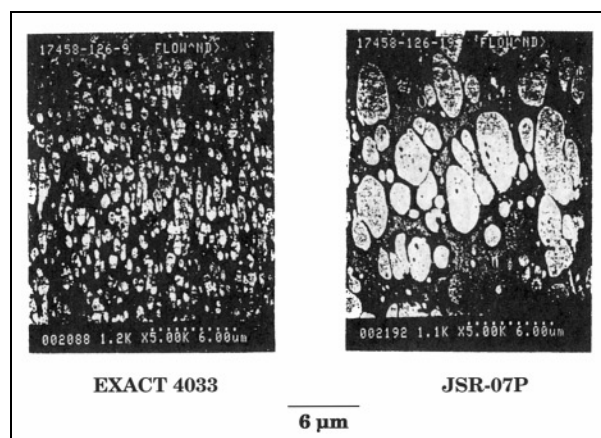


Figure 2.9 Low voltage scanning electron micrographs (LVSEM) of elastomer dispersions in polypropylene. Finer particle dispersions were obtained with an ethylene-butene plastomer (Exxon EXACT 4033, melt index 0.8g/10 min.; density 0.880 g/cc), left, than with a pelletized EPR rubber (JSR-07P, melt index 0.3g/10 min; density 0.864 g/cc), right, as the elastomeric phase. Elastomers (30 wt.%) were dispersed in 20 MFR isotactic polypropylene (Escorene PP 1105). Average particle sizes were 0.47 μm and 1.72 μm for the plastomer and EPR rubber, respectively. Magnification is 5000x. [801]

pylene rubber) were more compatible with the high flow rate polypropylene commonly used in molding large, complex parts in automotive applications, and lower melt flow rate suppression and higher impact strength were obtained. [801, 808, 800].

TPOs with more uniform particle dispersions have more consistent properties and higher knit-line strength. Dispersion of colors and additives into the resin is easier, and colors are cleaner. Resins with better dispersions can also have lower material densities and improved ductile properties. [814]

Depending on the formulation, thermoplastic olefins can be flexible or rigid; flexural moduli can range from 70 MPa (10,000 psi) to 2000 MPa (300,000 psi). Typical properties include high heat resistance, high melt flow, and superior low temperature impact resistance. Thermoplastic olefins can maintain ductile impact behavior at -34°C (-30°F). [807, 814]

In testing of equivalent 70 / 30 polypropylene / elastomer blends, plastomers doubled the weld-line strength and raised the melt index by up to 50% compared to EPDM, with a superior balance of flow and low-temperature impact properties. Plastomers maintained ductile behavior at -34°C (-30°F) with homopolymers of 4–35 g/10 minute melt flow indices, while EPDM and EPM blends were brittle with polypropylenes of 20 g/10 minute melt indices. [814]

Thermoplastic olefins are increasingly being used in the automobile industry, replacing traditional engineering thermoplastics due to their low cost, performance properties, and formulation flexibility. Internal and external automotive applications include bumper fascia, air dams, side body moldings, spoilers, mud flaps, wheel flares, and instrument panels. New TPOs for use in air bag covers have a useful temperature range of from -40°C (-40°F) to 100°C (212°F). TPOs containing 20–50% EPR are used in automotive, film, wire and cable, blow molding, and compounding applications; automotive grades can be formulated for superior paint adhesion. [801, 807, 812, 814]

2.5.6 Thermoplastic Vulcanizates

Thermoplastic vulcanizates (TPV), a type of thermoplastic elastomer, are a blend of a thermoplastic, usually polypropylene, and a rubber, similar to a thermoplastic olefin; however, the rubber phase in thermoplastic vulcanizates is crosslinked or vulcanized. EPDM is most commonly used as the elastomeric phase; other elastomers used include EPR rubber, butyl rubber, and natural rubber. [805,

809, 811] The elastomeric phase, consisting of small, 1–2 μm rubber particles, is dispersed in the continuous polypropylene matrix. [811] Elastomeric performance properties of the TPV are determined by the crosslinking of the elastomeric phase, while the polypropylene phase provides for melt processability. TPVs can be fully or partially crosslinked. [811, 805]

Properties of thermoplastic vulcanizates are similar to those of thermoset rubber. Rubber-like properties include hardness ranging from 35 Shore A to 50 Shore D, low compression and tension set, excellent fatigue resistance, and good energy dampening. Properties are retained in continuous use temperatures up to 135°C (275°F). Crosslinking also provides excellent resistance to polar fluids and ozone; resistance to nonpolar fluids such as oils and hydrocarbons is dependent on the nature of the elastomeric phase. [805, 811, 813]

Due to the pseudoplastic behavior of TPVs, they perform well in both extrusion and injection molding processes. Extrudate integrity is maintained during extrusion due to high viscosities at low shear rates, and the low viscosity at high shear rates allows the use of low injection pressures and shorter injection times. Larger rubber particle sizes and a lower degree of crosslinking lower the viscosity of the resin but also lower tensile strength and elastic recovery. A lower rubber phase concentration increases the resin viscosity less than a higher rubber phase concentration; elastomeric performance is also decreased. [811]

Thermoplastic vulcanizates are used in the automotive, construction, and medical industries. Automotive applications include CV joints and strut covers, rack and pinion boots, grommets, and ductwork. TPVs are used in the construction industry for plumbing hose, window gaskets, and geomembranes. [813]

TPVs are used in the medical industry as a replacement for thermoset rubber. Although natural rubber is the most widely used elastomer in medical applications, allergic reactions to natural rubber latex proteins and heightened biocompatibility concerns have prompted the use of alternatives. In addition, significant cost reduction can be achieved with TPVs. A 55-Shore-A TPV used in a 5 milliliter syringe tip instead of a thermoset rubber can result in a 25% reduction in material cost savings. The tighter tolerances in thermoplastic processing methods (injection molding and extrusion) in comparison to thermoset processing meth-

ods permit the use of increased line and assembly speeds and reduced thicknesses in thin-walled parts. In experimental studies, EPDM-polypropylene TPVs exhibited acceptable performance in mechanical properties (hardness, compression set,

sealing characteristics) and resistance to medical fluids and sterilization and exceptional performance in biocompatibility testing, passing the full battery of ISO 10993 tests. [809]

Commercial polypropylene resins contain various additives to stabilize the material during and after processing and to modify properties of the resin for use in a particular application. Additives are chemicals that are dispersed in the resin before or after processing, or that are applied to the finished part surface. Different additives provide resistance to oxidation, sterilization, and light degradation. Catalyst deactivators neutralize any remaining catalyst residues. Nucleators increase resin clarity and reduce processing time, and pigments provide a variety of colors. Antistatic agents permit the discharge of static electricity from the film or part, and the addition of flame retardants allows the use of polypropylene in electronics, construction, and transportation applications. Antiblock and slip agents are commonly used in films, to prevent films from sticking together or to metal surfaces or to prevent a film from sticking to itself. Specific applications, such as in the medical industry, require a combination of additives packages; interaction of additives can result in changes in polymer properties, such as discoloration. [825, 642, 795]

3.1 Antioxidants

Stabilization of polypropylene is essential in order to prevent oxidative degradation. (See *Oxidation* (1.134) under **Chemistry** (Chapter 1) for a description of oxidation reactions in polypropylene). Because of its high susceptibility to oxidation due to the pendant methyl group, unstabilized polypropylene can begin to decompose almost immediately after formation. At elevated temperatures and in the presence of air, polypropylene disintegrates to an oxidized powder. Oxidative degradation in polypropylene decreases the molecular weight (and increases melt flow), resulting in a decrease in viscosity. Embrittlement, surface cracking, and a loss of other mechanical properties can occur. Degradation products from oxidation reactions produce discoloration and loss of clarity. Polypropylene is usually stabilized immediately after polymerization. [817, 819, 820, 842]

Thermal oxidation is a free radical chain reaction initiated by the oxygen in air, heat, mechanical stress (shear), radiation, or metal residues. Interaction of any of these initiators with the polypropylene chain results in abstraction of a hy-

drogen atom along with an electron, producing a carbon atom with an unpaired electron (a free radical). Further reactions propagate the number of free radicals and form hydroperoxides, which decompose to produce chain scission. The chain reaction is terminated when two radicals combine to form an inactive product. [819, 820]

3.1.1 Primary antioxidants

Antioxidants inhibit the oxidation reaction by combining with free radicals or by reacting with hydroperoxides. Primary antioxidants, such as hindered phenolics and secondary aromatic amines, are radical scavengers. The reactive OH (hindered phenolic) or NH (secondary aromatic amine) group donates hydrogen to a carbon, oxygen, or peroxy free radical (Figure 3.1) to form a stable, inactive product. The aromatic ring structure and alkyl substituents (R) stabilize the free radical, which does not abstract hydrogen to propagate the reaction; however, it can undergo rearrangement and combine with another peroxy free radical to form an inactive product. [817, 819, 822]

Hindered phenolics are the most popular antioxidants used in polypropylene. The most common simple phenolic is butylated hydroxytoluene (2,6-di-*t*-butyl-4-methylphenol or BHT; Figure 3.2). BHT is FDA-approved but can exhibit volatility at high temperatures. Higher molecular weight phenolics are less volatile and are used when high processing temperatures are necessary or for high temperature applications. Thiobisphenolics are used primarily for resins exposed to extreme service ap-

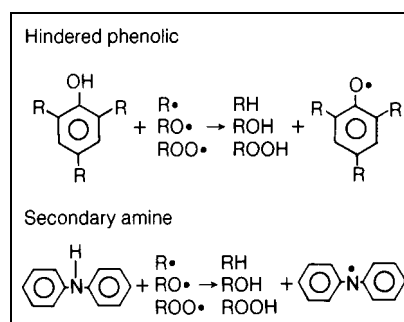


Figure 3.1 Stabilization reactions of primary antioxidants. A hindered phenol, top, or secondary amine, bottom, donates a hydrogen atom to a polypropylene (R•), alkoxy (RO•), or peroxy (ROO•) free radical to form a polypropylene (RH), alcohol (ROH), or hydroperoxide (ROOH) product. The phenolic (top) or amine (bottom) free radical formed can then combine with another free radical to form an inactive product. [819]

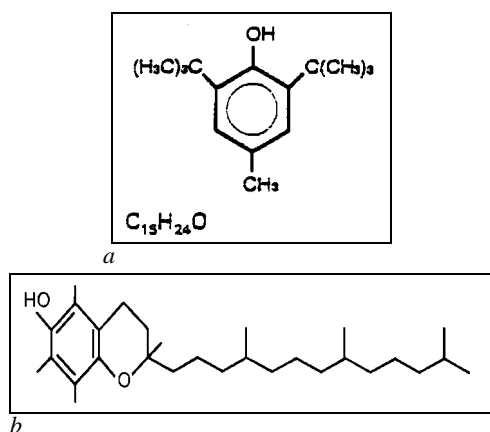


Figure 3.2 Molecular structures of commonly used phenolic primary antioxidants. a) BHT, 2,6-Bis-(1,1-dimethylethyl)-4-methyl-phenol (Ashland Chemical) b) α -tocopherol.

plications, such as in wire and cable. Due to enhanced susceptibility to oxidation, polypropylene requires higher levels of phenolic antioxidants than other polyolefins, usually 0.25–0.5%. Hindered amine light stabilizers, commonly used to stabilize polypropylene against the degradative effects of ultraviolet light, have recently begun to be used as substitutes for phenols. [824, 822]

α -tocopherol (ATP or vitamin E) reacts faster than other phenolics due to its less hindered molecular structure. The rapid reaction contributes to decreased taste and odor and good processing stability but increases the rate at which the antioxidant is consumed. ATP exists as a viscous amber oil and is inappropriate for resins with service temperatures over 150°C (302°F). It is more expensive than other antioxidants but can be used in concentrations (≤ 250 ppm; $\leq 0.025\%$) that are lower than other phenolics. [822, 823]

Phenolics generally resist staining and discoloration; however, when oxidized, they form quinone structures with conjugated double bonds. These structures are chromophores and absorb light to produce a yellow color in the resin. Phenolic oxidation can occur in the presence of metal Ziegler-Natta or metallocene catalyst residues; different residues or different amounts of the same catalyst residues can produce different degrees of yellowing. Trivalent phosphorus compounds and antacids (calcium stearate and zinc stearate) are used as co-additives to scavenge acidic catalyst residues. Phenolic oxidation and yellowing can also occur as a result of radiation sterilization or in the presence of gaseous atmospheric pollutants such as nitrogen oxides (gas fading or gas yellowing). High molecular weight phenolics, with

large, bulky substituents that interfere sterically with the phenolic oxidation reaction, are not as easily oxidized, resulting in less yellowing. [824, 822, 820, 692, 693, 817, 823, 819]

Secondary aromatic amines are primarily used in nitrile and butadiene rubbers and styrene butadiene rubber (SBR). They discolor easily and are limited to applications with pigments or carbon black, in which the discoloration can be masked. They are superior to phenolics for high-temperature applications, such as under-the-hood automotive applications but are not FDA-approved for food-contact use. [822, 825, 821]

3.1.2 Secondary antioxidants

Secondary antioxidants, also called peroxide decomposers, inhibit polypropylene oxidation by decomposing hydroperoxides. Phosphites and thioesters are the most common secondary antioxidants. Both types reduce hydroperoxides to a stable alcohol species in an oxidation-reduction reaction; the phosphite or thioester is oxidized to a phosphate or sulfoxide, respectively (Figure 3.3). The structures of several phosphite antioxidants are shown in Figure 3.4 [821, 819, 823]

Secondary antioxidants are usually combined with primary antioxidants for a synergistic effect; with the proper combination, the stabilization obtained is greater than the sum of the effect of each antioxidant alone. In addition, substitution of a secondary antioxidant for a portion of a more expensive primary antioxidant can provide equivalent stabilization and reduce additive costs. The stabilization obtained from secondary antioxidants alone is generally inadequate. A resin containing both pri-

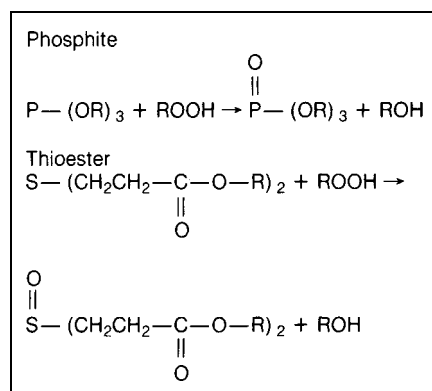


Figure 3.3 Stabilization reactions of secondary antioxidants. A phosphite or thioester compound reacts with a hydroperoxide, reducing it to an alcohol. The phosphite or thioester is oxidized to a phosphate or sulfoxide, respectively. In the reactions, R refers to an alkyl or aromatic functional group. [819]

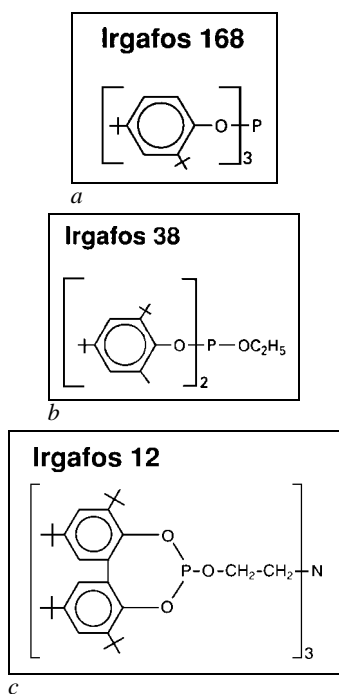


Figure 3.4 Structures of phosphite antioxidants. As secondary antioxidants, phosphites convert unstable hydroperoxides to alcohols. Antioxidants shown are: a) tris(2,4-di-tert-butylphenyl)phosphite b) bis[2,4-bis(1,1-dimethylethyl)-6-methylphenyl] ethyl ester, phosphorous acid c) 2,2',2"-nitriolo triethyl-tris[3,3', 5',5'-tetra-tert-butyl-1,1'-biphenyl-2,2'-diyl]phosphite. All are from Ciba-Geigy. [842]

mary and secondary antioxidants can vary in yellowness, depending on the particular secondary antioxidant used in the formulation. [821, 817, 692]

Phosphites are most commonly used as secondary antioxidants. Phosphites are nondiscoloring and are FDA-approved for many indirect food applications. They are highly effective process stabilizers and can minimize viscosity changes during processing. [822, 821]

A disadvantage of phosphites is their susceptibility to hydrolysis; they react with water to form acids. As a result, phosphites require careful storage and packaging. Impurities or "black specs" can appear in polymers containing hydrolytically unstable phosphites, and the acidic species formed can contribute to corrosion in steel processing equipment and can adversely affect the performance of hindered amine light stabilizers. Powders and granules can agglomerate, and screen pack plugging by partially hydrolyzed phosphites can result in a pressure build-up during extrusion processing. Newer phosphites contain bulky molecular groups around the phosphorus atom that sterically hinder the hydrolysis reaction; additives can also reduce the tendency to hydrolyze. Resistance to hydrolysis varies among

commercial grades; fluorophosponites are very hydrolysis-resistant. Use levels vary from 0.05–0.2% in polyolefins. [822, 821, 842]

Thioesters are used for long-term heat stability. They are nondiscoloring and FDA-accepted but can impart a taste and odor to the resin and can react antagonistically with hindered amine light stabilizers. Use levels range from 0.1–0.3% in polyolefins. [821, 822]

3.1.3 Antioxidant selection

Selection of the proper antioxidant or antioxidant combination depends on the performance required during processing and the application requirements. Characteristics of the antioxidant, such as physical form (solid, liquid), odor, discoloration potential, FDA-approval, hygroscopicity, volatility, and cost should be considered for optimal selection. Loading levels of the antioxidant should also be determined for the particular application. For example, if high melt stability is the primary requirement, a formulation composed of both primary and secondary antioxidants should contain higher levels of the primary antioxidant; for optimal color retention, however, the level of secondary antioxidant should be increased. Antioxidant suppliers generally provide additive packages containing blends of antioxidants and can tailor a system for a particular application. [819, 822]

High molecular weight phenolic antioxidants are preferred for applications requiring FDA approval, minimal discoloration, and long service life at high temperatures; secondary antioxidants are often incorporated into the formulation. A more economical, lower molecular weight phenolic antioxidant can be used in unstabilized polypropylene to provide adequate storage stability. [819]

Carbon black, used as a light stabilizer, may have an adverse effect on resistance to thermal oxidation; stabilizers such as hindered amines may be necessary for adequate protection. [842]

3.2 Acid scavengers

Acid scavengers or antacids are used in polypropylene to neutralize acidic catalyst residues. Calcium and zinc stearate are commonly used; other antacids include zeolites, calcium and zinc oxides, and metallic salts of lactic or benzoic acid. Antacids can affect other additives in the formulation, such as pigments, and metallic stearates can also act as mold release or slip agents. [883]

3.3 Metal deactivators

Metal deactivators are widely used in polyolefins to deactivate metal residues present in the formulation due to catalyst residues, impurities in additives (stabilizers, lubricants, pigments, fillers) or contact with copper, such as in wire and cable applications. Transition metals such as iron, cobalt, manganese, copper, and vanadium catalyze polypropylene oxidation by the decomposition of hydroperoxides, and antioxidants alone do not sufficiently reduce the metal-catalyzed oxidation rate. Use of metal deactivators is imperative in applications in which polypropylene comes in contact with copper — use as wire insulation or in parts with copper inserts. [857]

Metal deactivators function by chelation; they form a complex with the active metal species, substantially reducing its catalytic activity. Metal deactivators are organic molecules containing heteroatoms (nitrogen, oxygen, sulfur, phosphorus) and/or hydroxyl, carboxyl, or carbamide functional groups that can react with the metal; an example is N,N'-dibenzaloxalyldihydrazide. Metal deactivator concentrations in polyolefins for wire and cable applications range from 0.05–0.5%; polypropylene requires higher levels than polyethylene due to its increased susceptibility to oxidation. [857]

3.4 Light stabilizers

Unstabilized polypropylene deteriorates in the presence of sunlight, resulting in cracking, embrittlement, chalking, discoloration, and the loss of mechanical properties such as impact strength, tensile strength, and elongation. Outdoor applications are affected, in addition to indoor parts exposed to indirect sunlight. Photodegradation occurs as a result of ultraviolet light at wavelengths of 290–400 nm. In experiments, residual elongation at break of compression molded polypropylene sheet (1 mm; 0.04 in.) decreased to $\leq 50\%$ after about 1000 hours of ultraviolet light exposure. Different wavelengths may produce different types of degradation, depending on the polymer. [878, 863, 858]

Short-wavelength, high energy photons of ultraviolet light are absorbed by chromophores in the resin formulation. Chromophoric structures in polymers generally consist of double bonds between carbon atoms or especially between carbon and a heteroatom (such as oxygen). Saturated hydrocarbons such as polypropylene, with no double bonds, do not absorb light above 250 nm; however

impurities present in the formulation, such as catalyst residues, ketones, and hydroperoxides, or double bonds in the polymer introduced during manufacturing, act as chromophores. [878]

The photons of energy absorbed by chromophores raise the energy level of the chromophore. The chromophore is then in an excited state and must lose the excess energy to become stable again. The chromophore can release the excess energy as heat, fluorescence, or phosphorescence, or it can transfer the energy to another molecule (a quencher). Polymer degradation results from energy release by breaking molecular bonds (photolysis) and the formation of free radicals, highly reactive species having an unpaired electron. Free radicals of polypropylene, hydroxides, or hydroperoxides may be formed. [858, 878, 843]

The free radicals formed participate in oxidation reactions (See **1.3.4 oxidation** for a description of free radical reactions in polypropylene). The free radical chain reaction is initiated by the formation of free radicals in the absorbing chromophore; these free radicals then react with other molecules, producing new free radicals such as hydroxy, alkoxy, and peroxy (propagation). In chain branching reactions, more and more free radicals are formed, until chain termination reactions combine two free radicals to form inactive, stable molecules. Hydroperoxides are highly susceptible to photodegradation and decompose easily into free radicals, producing chain scission and a resulting loss of mechanical properties. [843]

Stabilization of the resin can occur by the use of additives that absorb ultraviolet radiation, preventing its absorption by molecules in the polypropylene resin, by free radical scavengers, by additives that decompose peroxides, or by quenchers that accept energy from the chromophore and convert it to heat.

3.4.1 UV absorbers

UV absorbers (UVAs) act as optical filters; they absorb ultraviolet light and release the excess energy as heat. UV absorbers are photostable molecules with high absorption in the wavelength range of 290 to 400 nm. Ideally, absorption should decrease dramatically after 400 nm, since absorption in the blue/violet part of the visible spectrum imparts a yellow color to the resin. UV absorbers commonly used in polypropylene include derivatives of benzophenone, benzotriazoles, aryl esters, and formamidines. Absorber substituents affect

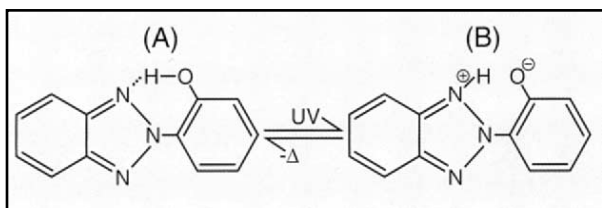


Figure 3.5 Tautomerism in ultraviolet absorbers.

Absorption of ultraviolet energy changes the electron distribution in the molecule from (A) to (B). The (B) tautomeric form then releases the energy as heat, and the electron distribution shifts back to form the (A) tautomer. The (A) tautomer can then absorb ultraviolet energy to repeat the process. The two tautomeric forms are in equilibrium and have the same atomic arrangement and molecular weight. [843]

properties such as compatibility to the resin, solubility, and volatility. The efficacy of UV absorbers in protecting the plastic is affected by part thickness; stabilization is more effective in thicker parts than in films, fibers, or sheets, and protection at the surface may be inadequate, even at high absorber concentrations. [858, 822, 863, 843]

UV absorbers are tautomeric molecules (Figure 3.5). Absorption of ultraviolet energy shifts the distribution of electrons in the molecule, while maintaining the same arrangement of atoms. The tautomeric forms, with different electron distributions, are in equilibrium and can easily interconvert. After releasing heat energy, the electron distribution rearranges to that of the original tautomer, which can again absorb UV energy. [843]

Benzophenones, such as 2-hydroxy-4-octoxybenzophenone (Figure 3.6), have moderate to strong absorption at wavelengths ranging from 230 to 390 nm. Early benzophenones displayed high volatility; however, recently-developed higher molecular weight substituents, such as octyl, decyl, and dodecyl groups, have reduced volatility and increased compatibility. [822]

Benzotriazole UV absorbers, based on 2-(2'-hydroxyphenyl)benzotriazole, show absorptions at 280–390 nm. They have a higher rate of UV absorption than benzophenones at similar loadings, and absorption drops off sharply at ~400 nm. Examples of benzotriazoles are shown in Figure 3.7. [878, 821, 822]

Phenyl or aryl esters, based on benzoic acid esters, are weakly absorbent but are converted to hydroxybenzophenones after exposure to ultraviolet light; absorption bands occur at 230–320 nm and 290–320 nm. Examples include salicylates, the first commercial UV stabilizers, resorcinol monobenzoates, and aryl or alkyl hydroxy benzo-

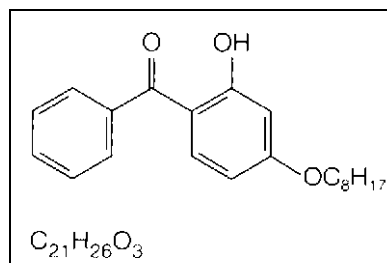


Figure 3.6 Structure of 2-hydroxy-4-octoxybenzophenone, a UV absorber used in polypropylene (Uvinul 3008; BASF). [863]

ates. They are FDA-approved for many applications. Although they display good initial color, discoloration may occur with some absorbers. They are less efficient than other light stabilizers but are less expensive. [878, 821, 822]

Other UV absorbers include formamidines, with absorptions at 290–320 nm, oxanilides, with absorptions from 280–320 nm, and acrylic esters, with absorptions from 290–320 nm. Absorption of acrylic esters drops off sharply at 400 nm, reducing yellowness, but acrylic esters are less effective than other absorbers and are rarely used. Oxanilides exhibit low color and low volatility and are used in applications that require high temperature processing. Their suitability for use with fluores-

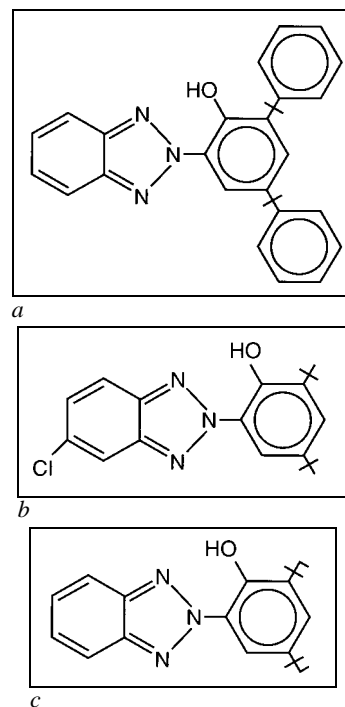


Figure 3.7 Examples of benzotriazole UV absorbers used in polypropylene. a) 2-(2H-Benzotriazol-2-yl)-4,6-bis(1-methyl-1-phenylethyl)phenol b) 2-(5-Chloro-2H-benzotriazol-2-yl)-6-(1,1-dimethylethyl)-4-methylphenol c) 2-(2H-Benzotriazol-2-yl)-4,6-bis(1,1-dimethylpropyl)phenol. (Tinuvin 234, 326, and 328; Ciba-Geigy)

cent pigments can reduce cost considerably in these applications. [822]

3.4.2 Quenchers

Quenchers are molecules that accept energy from an excited-state chromophore. The chromophore, after transferring its energy, reverts to the ground state, a stable energy state. The quencher dissipates the excess energy as heat, fluorescence, or phosphorescence, methods that do not result in resin degradation. Organic nickel complexes are commonly used as quenchers, such as [2,2'-thiobis(4-octylphenolato)]-n-butylamine nickel (II), nickel salts of thiocarbamate, and nickel complexes with alkylated phenol posphonates. [822]

Quenchers impart a green, yellow, or tan color to the resin and can only be used in applications in which color is not critical or can be masked. Quenchers are effective in highly pigmented resins and in thin sections such as films and fibers; they are frequently used in combination with UV absorbers. Quenchers are widely used in polyolefins. [822]

Nickel-based quenchers are used in agricultural film due to their resistance to pesticides. Government regulation of nickel compounds, due to safety concerns about heavy metal exposure, has resulted in decreased use of nickel quenchers. [821]

3.4.3 Peroxide decomposers

As in thermal oxidation, hydroperoxide decomposition is an important contributor to photooxidative degradation of polypropylene. Hydroperoxides are present in high concentrations in polypropylene (10^{-3} to 10^{-4} mole/ liter in fibers) relative to other absorbing compounds (carbonyl groups, ketones, catalyst residues); in the presence of light, they lose a hydrogen atom to form free radicals. Hydroperoxides have a high quantum yield (quantum yield ≈ 1), so that almost all photons of light absorbed by hydroperoxides result in the formation of free radicals. Quantum yield is the number of reactant molecules that react to form a product (a free radical in photooxidation reactions) for each photon absorbed. Molecules with lower quantum yields dissipate more excess energy through other methods, such as heat generation, than through chemical reactions. Decomposition of the hydroperoxide radical results in polypropylene chain scission and a reduction in mechanical properties. Peroxide decomposers act to decompose hydroperoxides into stable molecules such as alcohols before they can react with light to form free radicals. [858, 822]

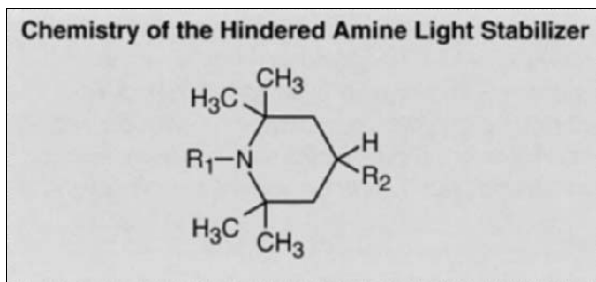


Figure 3.8 The structure of tetramethyl piperidine, the basic structure for hindered amine light stabilizers. R1, R2, and R3 are organic functional groups containing carbon and/or heteroatoms (See Figure 3.9 for examples of commonly used hindered amine light stabilizers). [843]

3.4.4 Free radical scavengers

Free radical scavengers are similar to the secondary antioxidants used to inhibit thermal oxidation; they react with free radicals in the polypropylene formulation, reducing them to stable, unreactive products. Hindered amine light stabilizers (HALS), introduced in the 1970s, function mainly as free radical scavengers, although they also may act as quenchers or peroxide decomposers. They dominate the market for light stabilizers and are now also used as thermal antioxidants. Hindered amines are derived from the structure of tetramethyl piperidine (Figure 3.8) and

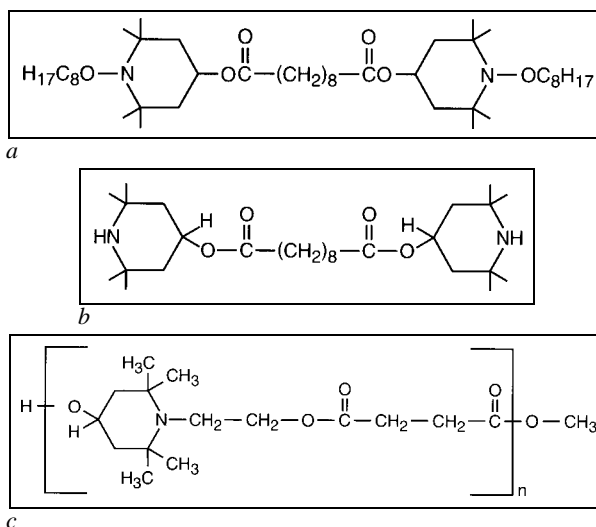


Figure 3.9 Examples of hindered amines used as free radical scavengers in polypropylene. a) bis-(1-octyloxy-2,2,6,6-tetramethyl-4-piperidinyl) sebacate (Tinuvin 123) b) bis(2,2,6,6-tetramethyl-1-piperidinyl) sebacate (Tinuvin 770) c) dimethyl succinate polymer with 4-hydroxy-2,2,6,6-tetramethyl-1-piperidineethanol (Tinuvin 622) All are from Ciba-Geigy. Low basicity hindered amines (a) are used in flame retardant fibers and tapes; (b) is used in thick sections. Oligomers (c) are high molecular weight HALS used in applications requiring low volatility. [843]

are very effective stabilizers at low concentrations (0.1%). Examples of commonly used HALS are shown in Figure 3.9. [843]

The exact stabilization mechanism of hindered amines is not known; it has been proposed that they scavenge free radicals through a regenerative mechanism shown in Figure 3.10. The hindered amine first oxidizes, forming a nitroxyl radical that reacts with a polypropylene or other free radical to form an alkoxy amine. This species then reacts with a peroxy radical to regenerate the original hindered amine, which begins the cycle again. [843]

HALS are available in a wide variety of molecular weights. They display low volatility and good stability at high temperatures. They can provide surface protection and can be used alone or in combination with UV absorbers and quenchers. They are extraction-resistant and are more compatible with the resin than benzophenones or nickel complexes. Although they are more expensive than UV absorbers, they are more cost effective due to lower use levels. Use levels vary with substrate thickness, pigmentation, and application requirements; levels generally range from 0.1–1.5%. [822, 821, 843, 878]

Hindered amines can interact with other additives in the formulation. Although HALS do not impart color to the resin; they do react with phenolic antioxidants to produce deep yellow colors after radiation sterilization. Discoloration can also occur in the presence of titanium dioxide pig-

ments, which are photoreduced by ultraviolet light at 350–400 nm. Oxidation products from this reaction can react with BHT in the basic environment provided by hindered amines to produce long-lived free radicals. These radicals then couple to form yellow oxidation products. [884, 823, 699]

Thioester antioxidants can negatively affect the free radical scavenging activity of HALS. Organic phosphites, which act synergistically with HALS, can be used to reduce the effect of thioesters. [878]

Interaction with halogenated flame retardants can deactivate HALS; acid generated by the flame retardant reacts with the basic amine structure and interrupts the free radical scavenging reactions. The destabilizing effects of halogenated flame retardants can be reduced by using a hindered amine with lower basicity (Figure 3.9) or by using a UV absorber to provide a screen for the HALS, by reducing the amount of acid generation. [837]

Due to their effectiveness, hindered amines have been substituted for UV absorbers in applications such as food packaging. Because stabilization is through a chemical reaction, they are not limited to thicker sections, such as outdoor seating and trash receptacles, but can be used in applications with high surface-to-volume ratios, such as films, slit tapes, and fibers. Their resistance to pesticides makes them useful in agricultural film. High molecular weight HALS are used in tapes and fibers, due to the tendency of low molecular weight stabilizers to volatilize or migrate out of the resin during processing, post-extrusion treatment, or long-term exposure. [821, 843]

HALS are widely used in stabilizing polypropylene for automotive applications. Low molecular weight monomers can be used in thick sections such as bumpers, which require HALS migration toward the part surface for effective stabilization. Monomers, however, can be lost from the surface through evaporation or extracted by fluids such as detergents or rain. In talc- or calcium carbonate-filled resins, monomers are partially absorbed by the filler, resulting in a loss of stabilization. A monomer-oligomer blend, with different migration rates, can reduce the loss of stabilization, but physical properties and molecular weights exhibit a discontinuity. High molecular weight HALS are used in thin sections, such as fibers for upholstery, cover seats, and door panels, where migration to the surface must be minimized. A new polysiloxane-based HALS, with molecular weights appropriate for the application, provided enhanced sta-

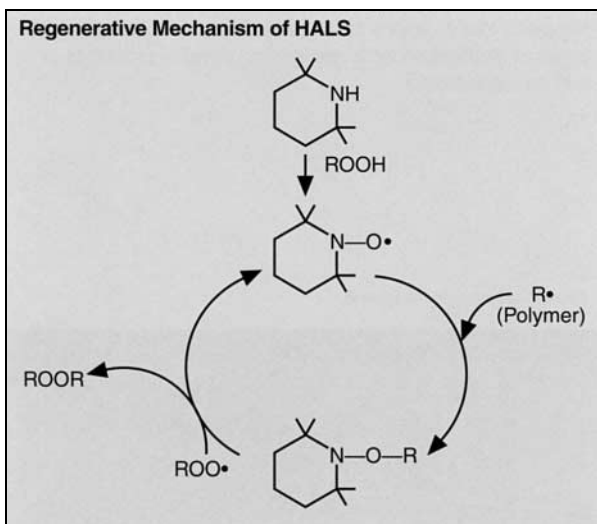


Figure 3.10 The stabilization mechanism of HALS. The amine is oxidized by reaction with a hydroperoxide to form a nitroxyl radical ($\text{NO}\bullet$); this then reacts with a polymer or impurity free radical ($\text{R}\bullet$) to form an alkoxy amine (NOR). The alkoxy amine reacts with peroxy free radicals to regenerate the nitroxyl radical ($\text{NO}\bullet$), which can then repeat the cycle. [843]

bilization in experimental studies and had lower volatility and extractibility. It was not absorbed by fibers present in the formulation and did not interact with pigments during fiber spinning. [885]

3.4.5 Screeners

Pigments added to a formulation to provide opacity or translucence, such as carbon black, titanium dioxide, and zinc oxide, act as UV screeners by absorbing or reflecting ultraviolet light. Carbon black absorbs ultraviolet and visible light throughout the entire spectrum and may also act as a free radical scavenger. It can be used at concentrations as low as 1 – 2%. The stabilization of resins containing carbon black can be enhanced by addition of antioxidants or HALS. Titanium dioxide (rutile) reflects light and is effective at high loadings. Some pigments can act as synergists with compounds such as phosphites and nickel-organic salts to improve embrittlement time for polypropylene by over 60%. [822, 878]

3.4.6 Evaluation of UV stability

The most accurate test of UV stability is use of the material in its intended end-use environment over a period of time. Due to the long-term nature of outdoor weathering tests, accelerated testing using artificial light sources (xenon arc lamp, sunshine carbon arc lamp, mercury arc lamp, fluorescent sun lamp) is common. Filtered xenon most accurately reproduces the spectral energy distribution of sunlight, while light sources with significant emission below 290 nm can produce different results than those obtained with long-term, outdoor weathering. Accelerated exposure tests may underestimate the effectiveness of HALS due to the very high levels of UV radiation produced. [819, 821, 843, 885]

3.4.7 Use of light stabilizers

Use levels of light stabilizers range from 0.05–2.0%, depending on the type of stabilizer, part thickness, presence of other additives, type of resin, and application requirements. Benzophenones and hindered amines are widely used in polypropylene. A combination of stabilizers is used to obtain the desired stabilization; highly stabilized polypropylene contains an ultraviolet absorber, a phosphite stabilizer, and a nickel quencher or hindered amine. [821, 878, 822]

Compatibility with the resin is more important in light stabilizers than in antioxidants, since they are used at higher concentrations. Higher concen-

trations of stabilizers can be dissolved at high temperatures than at low temperatures, so that stabilizers dissolved during resin processing may exhibit blooming, migration of the stabilizer to the part surface, when the resin is cooled. Blooming and turbidity can occur if the stabilizer is incompatible with the resin; compatibility of the generally polar light stabilizers is more difficult to achieve with nonpolar resins such as polypropylene. Diffusion of additives through the resin decreases in resins with increased crystallinity, crosslinking, or orientation. Low molecular weight stabilizers can migrate in incompatible resins; migration is considerably reduced with high molecular weight stabilizers. [858]

3.5 Nucleating agents

Nucleating agents are added to polypropylene to improve processing characteristics and clarity and alter its mechanical properties. The addition of nucleating agents provides a large number of sites for the initiation of crystallization, so that spherulites formed are smaller and more numerous than in unnucleated polypropylene (See Figure 2.2 in Chapter 2: Morphology for a comparison of spherulite sizes in nucleated and unnucleated polypropylene). Spherulite crystallization around a nucleating agent is shown in Figure 3.11. [886, 693]

Nucleation increases the crystallization temperature and the rate of crystallization; as a result, parts can be removed from the mold at higher temperatures, and molding cycle times are reduced. Crystallization is more complete in nucleated resins than in unnucleated resins, producing high levels of

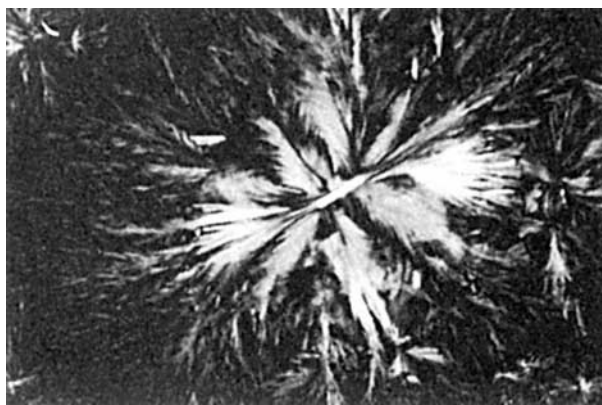


Figure 3.11 Micrograph of a spherulite of polypropylene formed in the presence of a nucleating agent. The nucleating agent is at the center of the spherulite, suggesting that the nucleating agent initiated crystal formation. The nucleating agent was sodium 2,2'-methylenebis(4,6-di-tert-butylphenyl) phosphate. [886]

crystallinity. Nucleated materials have higher tensile strength, stiffness, flexural moduli and heat deflection temperatures than unnucleated materials, but impact strength is lower. The high levels of crystallinity can result in reduced tolerance to radiation sterilization compared to unnucleated polypropylene, and the effectiveness of hindered amine light stabilizers and other stabilizing additives can be reduced. Because nucleated polypropylene shrinks more rapidly in the mold, shrinkage of the resin onto mold cores can occur if parts are not ejected fast enough. [696, 693, 67]

Clarity is enhanced due to the increased cooling rate and the decreased spherulite size, which reduces the scattering of light as it passes through the material (See 2.3.4 *haze* for an explanation of haze in unnucleated polypropylene). Smaller spherulites can reduce warpage in some applications and can provide a harder, more stain-resistant surface. [696, 693]

Nucleating agents used in polypropylene include carboxylic acid salts, benzyl sorbitols, and salts of organic phosphates. Carboxylic acid salts provide limited clarity enhancement but do enhance the mechanical properties by an increase in the crystallization rate. Dibenzylidene sorbitols reduce crystal size dramatically, resulting in greatly improved clarity. Benzyl sorbitols can result in odor generation during processing which produces odor in the finished part. Pigments, such as phthaloxyanine blue and green and phthalyl blue, and mineral fillers such as talc can also act as nucleating agents, although talc is not as effective. [693, 886, 779, 696]

Applications of nucleated polypropylene include food bottles and packaging, automobile parts, medical syringes, and houseware containers. [855]

3.6 Flame retardants

Many plastics are inherently flammable due to their origins in petroleum manufacturing. Polypropylene ignites when in contact with a flame and burns with a faintly luminous flame even after the ignition source is removed. Melting occurs due to the high heat of the flame, producing burning drips. For applications in the construction, automotive, appliances, and electronics industries, polypropylene must be stabilized by the use of flame retardants. [825, 820, 326]

Polypropylene is one of the most difficult plastics to make flame retardant. High levels of

flame retardants are required in the polypropylene formulation to meet standards for applications such as in the electronics industry; 25% flame retardant is required in polypropylene compared to 10–20% for styrenics or engineering thermoplastics. These high levels of flame retardant increase brittleness and impair the mechanical performance of the material. Flame retardants can also reduce processability and can interfere with the action of other additives, such as hindered amine light stabilizers. [834, 836, 837]

3.6.1 Fire

Combustion is a highly exothermic reaction, in which hydrocarbons are oxidized to carbon dioxide and water. Combustion is a gas-phase reaction — polypropylene or its decomposition products must become gaseous for a fire to begin. Fire in a candle occurs when melting wax (composed of hydrocarbons) migrates up the wick through capillary action and is pyrolyzed at 600–800°C (1100–1500°F) to gaseous hydrocarbon decomposition products (Figure 3.12). Pyrolysis is the decomposition of a material by heat alone (in the absence of oxygen). Some of the gaseous hydrocarbons are converted to soot; smoke consists of suspended soot particles. Reaction with carbon dioxide and water in the luminous region produces carbon monoxide. Most of the gaseous hydrocarbons react with oxygen at the exterior of the flame to produce heat, which melts more wax and begins the cycle again. [768, 828, 662, 896]

A fully developed, damaging fire results when

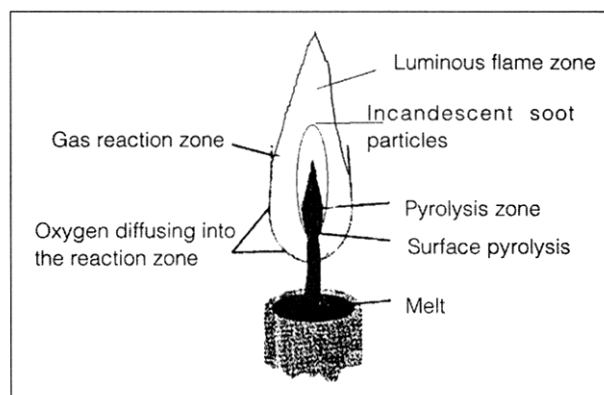


Figure 3.12 A candle flame. Melting wax migrates up the wick and pyrolyzes at the surface of the wick to form gaseous hydrocarbon decomposition products. Some of the gaseous hydrocarbons form soot in the incandescent region of the flame; gases can also react with water and carbon dioxide in air, forming carbon monoxide in the luminous flame zone. Most gases react with oxygen at the exterior of the flame to produce heat. [896]

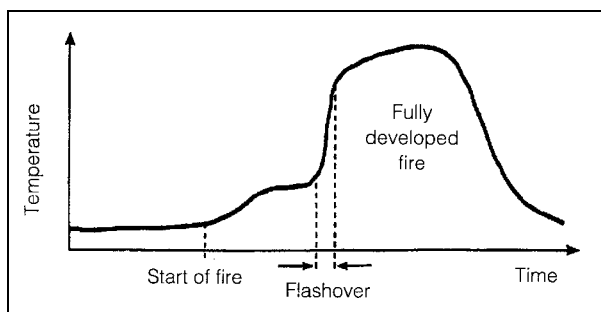
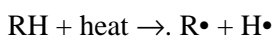


Figure 3.13 Temperature changes during stages of a fire. A spark ignites combustible material, starting a fire. As this material pyrolyzes, flammable gases are produced, and the temperature increases slightly. Flashover occurs as these gases ignite, spreading the fire and dramatically increasing the temperature. The fully developed fire burns and spreads until it has reached its peak; the temperature then diminishes as the fire goes out. [896]

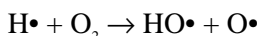
an initial ignition source, such as a cigarette or spark, ignites combustible material (i.e. paper). The heat generated from this fire radiates out to other combustible materials (curtains, carpeting), which pyrolyze to produce a flammable gas mixture. Flashover (Figure 3.13) occurs when these gases ignite, instantly spreading the fire over the entire area and producing a room temperature of over 1000°C (1800°F). The fire spreads further until it has reached its peak, then diminishes. [896, 828]

Polypropylene begins to decompose at temperatures ranging from 320 to 400°C (610–750°F), forming gaseous decomposition products which initiate combustion. Only small amounts of soot are formed during polypropylene combustion. Soot is composed of aromatic compounds derived from the decomposition of polymers such as SAN or polyphenylene ether, that contain aromatic rings in their molecular structure. Polymers containing oxygen, such as PPO and polycarbonate, tend to decompose to form a carbonaceous char; polypropylene, with no oxygen atoms in its molecular structure, forms little char during decomposition. [835, 828, 662]

Combustion is a free radical, exothermic chain reaction. At high temperatures, hydrogen, along with one electron of the covalent bond, is abstracted from a carbon atom in the hydrocarbon decomposition products of polypropylene (RH), resulting in the formation of a hydrogen free radical (H•) and a carbon free radical in the hydrocarbon gas (R•):



Reaction with oxygen in the air forms hydroxy radicals:



Reaction of the hydroxy radicals with carbon monoxide (CO) then forms carbon dioxide (CO₂) and another hydrogen radical. This reaction is highly exothermic:



The hydrogen radical can then react with O₂ to propagate the reaction. [828]

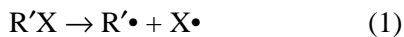
The generation of heat and free radicals provides energy for the combustion reaction. If more energy is produced than is required, the combustion rate increases until flashover occurs. If too little energy is produced to sustain combustion, the reaction rate continually decreases until combustion ends. [828]

Flame retardants reduce the ignitability and combustion rate of the polymer. Some flame retardants scavenge free radicals in the combustion reaction. Others create a protective layer between the condensed (solid) polymer and the gaseous decomposition products in order to limit heat transfer to the solid polymer, cooling it and reducing decomposition. Other flame retardants undergo endothermic decomposition reactions that form nonflammable gases. The pyrolysis gases are then diluted, and the endothermic reaction takes in heat and cools the hot polymer to a temperature below its decomposition temperature, so that lower amounts of pyrolysis gases are formed. [829, 828, 825]

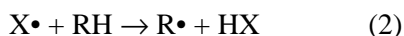
Flame retardants can be reactive or additive. Reactive flame retardants, used mainly in thermosets, are chemically bound to the polymer; additive flame retardants, used primarily in thermoplastics, are physically mixed with the resin during or after polymerization. [828, 825]

3.6.2 Free radical scavengers

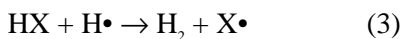
Organic compounds containing halogens (bromine or chlorine) function in the gas phase of the combustion reaction by scavenging free radicals formed during combustion. At pyrolysis temperatures, halogen flame retardants dissociate to form free radicals:



in which X = Br or Cl and R' = the organic part of the molecule, with an unpaired electron on a carbon atom. The halogen free radical then abstracts a hydrogen from the gaseous hydrocarbon (RH), forming a free radical (R•) and the active flame retardant species, hydrogen halide (HX):



The hydrogen halide interferes with the free radical combustion reaction by reacting with the $\text{H}\cdot$ and $\text{HO}\cdot$ radicals to produce lower energy $\text{X}\cdot$ radicals:



The hydrogen halide can then react with the decomposition gases (2) to repeat the cycle. [829, 828]

The efficacy of halogen flame retardants increases in the order: $\text{F} < \text{Cl} < \text{Br} < \text{I}$. Although iodine (I) is most effective, it is thermally and photolytically unstable due to weak bonding to carbon atoms in the organic flame retardant molecule ($\text{R}'\text{X}$), and dissociation occurs before pyrolysis temperatures are reached. Fluorine (F) flame retardants are ineffective due to the strong bond between carbon and halogen, making dissociation (Reaction 1) more difficult. Bromine and chlorine are used in flame retardants; bromine is more effective and more widely used due to the weaker $\text{R}'\text{-Br}$ bond. [828, 829]

Brominated flame retardants can be aliphatic, aromatic, or ionic. Aromatic bromines, such as decabromodiphenyl oxide, also called decabromodiphenyl ether, and octabromodiphenyl oxide, are commonly used in polyolefins; aliphatic bromines, such as stabilized hexabromocyclododecane, have also been used. Some aliphatic and aromatic bromines used in polypropylene are shown in Figure 3.14. Decabromodiphenyl oxide is insoluble in polypropylene and acts as a filler. Aromatic bromines are more thermally stable than aliphatic bromines, which can decompose during processing; however, aromatic bromines are more susceptible to photo-initiated bond cleavage and may exhibit surface blooming. Brominated flame retardants are usually white powders, with bromine contents of up to 85%. [830, 837, 822, 844]

Cycloaliphatic chlorines are used as flame retardants in polypropylene. They are supplied as a white solid with 65% chlorine and are more heat resistant than other chlorinated flame retardants, such as chlorinated paraffins. [825, 822] Ionic flame retardants (ammonium bromide, phosphonium bromide) are used in cellulose and thermoplastics. [827]

Antimony trioxide (Sb_2O_3) is generally added to halogenated flame retardants for a synergistic effect. Although antimony trioxide alone has no flame retardant properties, it reacts with hydrogen halides to form antimony trihalides and antimony oxychlorides, which, along with HX , scavenge $\text{H}\cdot$

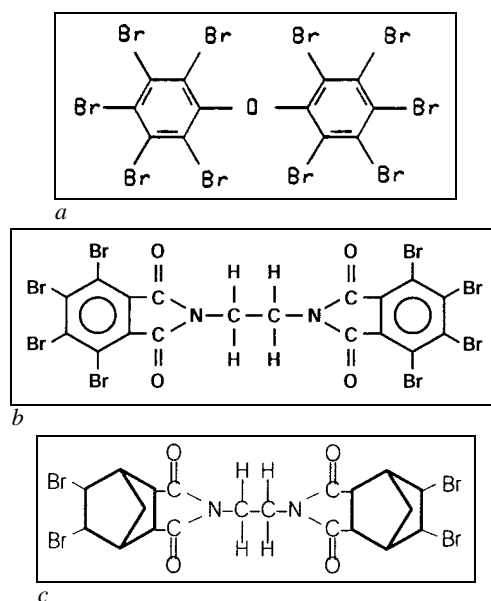


Figure 3.14 Examples of brominated flame retardants used in polypropylene. a) decabromodiphenyl oxide b) ethylenebistetrabromophthalimide c) ethylenebis(dibromonorbornanedicarboximide) (DE-83R, Great Lakes Chemical, SAYTEX BT and SAYTEX BN-451, Albemarle) [844, 831]

and $\text{HO}\cdot$ free radicals in the combustion reaction. Antimony oxide is a white powder that can produce dust during handling; nondusting grades are available. It acts as a pigment in the plastic, having a whitening effect, and its particle size can affect processing, physical properties, and pigmentation. [830, 822, 829]

Other synergists include ferric oxide, zinc oxide, zinc borate, and barium metaborates. They can be used in addition to antimony oxide, to increase the synergistic effect; zinc borate has been used as a partial or complete replacement for antimony oxide in polyolefins. Zinc borate is less expensive than antimony oxide and also functions as a smoke suppressant, afterglow suppressant, and antiarcing agent. Its refractive index is similar to most polymers, permitting translucency in the plastic. [830, 822]

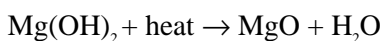
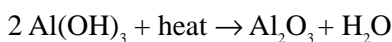
Problems with halogenated flame retardants include interaction with hindered amine light stabilizers, corrosion due to production of gaseous, acidic hydrogen halides, and potentially toxic decomposition products. At high processing temperatures or in the presence of UV light, halogenated flame retardants can dissociate to free radicals, resulting in the production of hydrobromic or hydrochloric acid (reaction 2), which can then react with the basic hindered amines and reduce their stabilizing effect.

tiveness. Use of UV absorbers or less basic hindered amines may alleviate the effect. [883, 837]

Restrictions on brominated flame retardants are increasing due to possible environmental and health risks of brominated diphenyl ethers, which can under some conditions form brominated dioxins and furans. Selected diphenyl ethers have been restricted in Germany, and demand for non-halogen flame retardants is increasing. [875, 828]

3.6.3 Magnesium hydroxide and aluminum hydroxide

Magnesium hydroxide and aluminum hydroxide, also called aluminum trihydrate (ATH), decompose in the presence of heat, forming water and metal oxides:



The water vapor mixes with and dilutes the combustion gases, and the endothermic reaction takes in heat from the burning plastic. In addition, the hydroxide particles act as a filler in the plastic material, diluting the polymer, and the solid aluminum or magnesium oxide formed during decomposition provides an insulating char layer on the plastic surface. [828, 832]

For effective flame inhibition, the flame retardant must decompose at a temperature similar to that of the polymer. Magnesium hydroxide, with a decomposition temperature (T_d) range of 250–340°C (482–640°F), is commonly used in polypropylene ($T_d = 320\text{--}400^\circ\text{C}$; 610–750°F). Use of magnesium hydroxide requires careful attention to processing, since its decomposition temperature is also in the range of polypropylene processing temperatures. Aluminum hydroxide begins to decompose at ~230°C (440°F); it is widely used in thermosets, although surface-treated grades are used in polypropylene. High loadings of magnesium oxide (50–65%) are necessary for adequate flame protection in polypropylene. At lower loadings, it functions mainly as a smoke suppressant. The high loadings required may negatively affect impact properties. Because polypropylene is nonpolar, surface treatment or coupling agents, such as fatty acids or modified polyolefins, are added to the formulation to improve processing and produce more uniform blends. Surface treatment can reduce dusting and improve translucence, wetout, rheology, and product performance. [822, 830, 828, 834, 833, 822]

Aluminum and magnesium hydroxides are available in various particle sizes; aluminum hydroxide particle sizes range from 5–20 μm . Magnesium carbonate is used as a smoke suppressant, functioning through the same endothermic decomposition mechanism as the hydroxide. Both magnesium compounds can be used with ATH for a synergistic effect. [824, 822]

3.6.4 Phosphorus

Phosphorus flame retardants are most useful in oxygenated polymers such as thermosets. They function in the condensed phase by thermally decomposing to phosphoric acids during combustion, which catalyze the evolution of water from the oxygen-containing polymer and form a carbonaceous char. They are not generally effective in materials that do not form char during combustion, such as polyolefins; however, specialty grades containing phosphate salts can be used in polypropylene. Phosphorus compounds can be halogenated to increase the flame retardant effect. [835, 822]

Phosphate salts composed of ammonium polyphosphate, a polyhydric alcohol, and a nitrogen source form an intumescent system that produces a cellular char when activated by heat. Thickness increases of 700–800% are common in coatings used for public buildings and nuclear installations. The foamed char insulates the plastic from the flame, and phosphoric acids formed during decomposition catalyze the evolution of water from the polyhydric alcohol. [835]

Alkyl amine acid phosphate (EDAP) is a phosphate salt effective in polypropylene; a UL 94 VO rating (at 3.2 or 1.6 mm; 0.12 or 0.062 in.) is achieved at loadings of 30–40 weight percent. Synergists such as pentaerythritol, which reduce thermal stability and form incompatible acids during processing, are unnecessary. Higher loadings are required for polymers of decreasing molecular weight (higher melt flow), due to polymer flow during burning that results in flaming drips in the UL 94 vertical burn test. Blends of EDAP with nitrogen compounds greatly increase the flame retardant effect, and UL 94 compliance can be attained by loadings 15–25% lower than EDAP alone; physical properties of the resin are also retained. [835]

3.6.5 Test methods

Flammability tests have been developed to measure the burning parameters, such as burning time, dripping, smoke emission, and flame spread, of a mate-

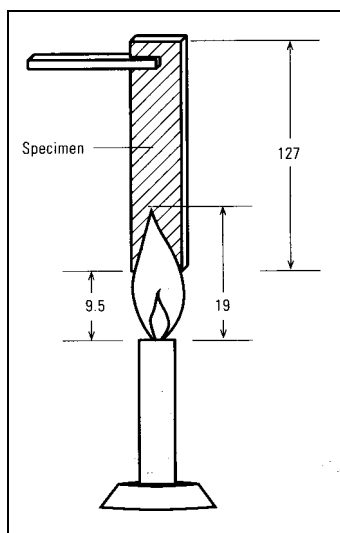


Figure 3.15 The UL 94 vertical burn test. A specimen suspended vertically over absorbent cotton is ignited by a bunsen burner. Duration of the flame and afterglow is measured, and any generation of flaming drips that ignite the cotton is noted. Each of five samples are ignited for 10 seconds; rating criteria include V-0, V-1, V-2, V-5, and HB levels. [888]

rial under specified conditions, in order to predict its performance in an actual fire. Many applications require specific performance levels in particular tests. The most common test is the UL 94 in electrical devices, in which burning times resulting from various ignition orientations are measured. The purpose of the test is to ensure that a spark or electrical short will not result in a fire. In the UL 94 V test (Figure 3.15), a specimen is suspended vertically over a bunsen burner and surgical cotton. The results rate the specimen at different levels based on thicknesses; a V-0 rating, the highest, corresponds to a flame duration of 0–5 seconds, an afterglow of 0–25 seconds, and no flaming drips that ignite the absorbent cotton. [828, 662]

In the limiting oxygen index (LOI) test, the minimum concentration of oxygen necessary for candle-like burning of ≥ 3 minutes is measured. It is primarily used for product development. Numerical data are obtained, and the LOI is generally directly proportional to the concentration of flame retardants. A higher LOI indicates that more oxygen is needed to support combustion. Air contains $\sim 21\%$ oxygen, so a rating lower than this will usually support combustion under normal atmospheric conditions. [662, 828]

Combinations of flame retardants are generally used to achieve the required level of fire inhibition. A V-0 or V-1 (≤ 30 s flame duration, ≤ 60 s afterglow, no cotton ignition) rating can be

achieved in polypropylene with $\geq 30\%$ of a cycloaliphatic chlorine and $\geq 13\%$ antimony oxide. A V-2 rating (≤ 30 s flame duration, ≤ 60 s afterglow, cotton ignition) can be achieved with 5–10% brominated cycloaliphatic imides, ammonium fluoroborates, or chlorinated polyolefins, with an antimony oxide synergist. [822]

3.7 Colorants

Color is used in almost all plastic applications. Color can improve the aesthetic appeal of a product — qualities such as “warm”, “soft”, “bright”, or “pleasant” are determined primarily by color. Product color influences consumer perception and can determine how well the product sells, and color changes may be necessary over time as consumer preferences change. A variety of colors are available for use in plastics, in addition to special effect colorants that produce metallic effects, pearlescence, fluorescence, and phosphorescence. [871, 821, 824]

Colorants used in plastics are pigments or dyes. Dyes are organic compounds that are soluble in the plastic, forming a molecular solution. They produce bright, intense colors and are transparent and easy to disperse and process. They can have poor thermal and UV stability, however, and are mainly used in applications with low processing temperatures and low UV stability requirements, such as toys. Dyes are not compatible with polyolefins, having a tendency to bleed and plate out, but they have been used in oriented or crosslinked polypropylene. [826, 871]

Pigments are generally insoluble in the plastic; color results from the dispersion of fine particles (~ 0.01 – $1\ \mu\text{m}$) throughout the resin. They produce opacity or translucence in the final product. Pigments can be organic or inorganic compounds, and they are available in a variety of forms — dry powders, color concentrates, liquids, and precolored resins. [821, 826]

3.7.1 Optical effects of pigments

Pigments and dyes produce color in a resin from selective absorption of visible light (wavelength range from ~ 380 nm (violet) to 760 nm (red)). The perceived color is the color of the light transmitted through the colorant and not the light that was absorbed. Complementary colors are seen by the eye; light absorption at 490 – 560 nm (green) will be perceived as a red color. (Complementary colors

are red-green, blue-orange, violet-yellow). The human eye can detect color differences of about 1 nm in wavelength. Absorption at all wavelengths of visible light will produce a black color, while no absorption will appear colorless. [766, 590]

Because dyes are in solution, color is produced only from light absorption, and the material is transparent. A dispersion of pigment particles in a resin can also reflect or scatter light. If the refractive index of the pigment particle is different from that of the spherulites in the plastic microstructure, light will be reflected, and the particle dispersion will scatter light in all directions. Light reflection and scattering produces opacity in an originally transparent resin. Resins can be colored and opaque if light was absorbed only at particular wavelengths, or white and opaque if all light was reflected (no absorption). The color shade is affected by particle size of the pigment. Ultramarine blue pigments are nonreflective due to a refractive index similar to that of the plastic. [859]

3.7.2 Pigment characteristics

Pigments must be adequately dispersed in the resin for optimum light scattering; specks and uneven coloration can result from incomplete dispersion. Primary pigment particles tend to agglomerate; these must be broken up and distributed homogeneously throughout the polymer during processing, usually by viscous forces or milling. The presence of agglomerated pigment particles in the final part can result in brittleness and part breakage, and large particle sizes can dramatically decrease Gardner impact strength — the large pigment particles act as stress concentrators that reduce the energy required for crack initiation. Higher shear forces can produce pigments with smaller particle sizes. [871, 825, 840, 820]

Pigments should be compatible with the polymer; poor compatibility can be a cause of part failure. Some pigments are partially soluble in the resin and can migrate through the polymer to the surface, where they rub off. Pigments must also be compatible with any other additives present in the formulation. Slip or antistatic agents can cause migration of some colorants. [819]

Most pigments exhibit good light stability, but fading, color changes, or degradation can occur, especially in the presence of both sunlight and humidity. Some colorants, such as FD&C lakes (FDA-approved), can fade even under fluorescent

lights. Surface treatments can improve weathering resistance. [819]

High temperatures during processing can damage or destroy the pigment, causing changes in shade or loss of color. Thermal sensitivity is related to both temperature and duration of exposure — long cycles in injection molding or rotational molding can have a more adverse effect than high-speed extrusion. [871]

Some pigments can act as nucleating agents, altering the mechanical properties and improving the clarity of the resin. In studies with colored filaments, phthalyl blue was found to be an effective nucleator; titanium dioxide (rutile) and carbon black (furnace black) were less effective. [779]

3.7.3 Inorganic pigments

The most common inorganic pigments include oxides, sulfides, chromates and other complexes based on heavy metals such as cadmium, zinc, titanium, lead, and molybdenum. They are generally more thermally stable than organic pigments and are more opaque and resistant to migration, chemicals, and fading. They can cause wear on processing equipment such as extrusion machine screws and barrels. The use of heavy metals has been restricted due to OSHA regulations; alternative formulations have been developed, but cost can be up to eight times that of heavy metal pigments, especially for bright colors. [825, 820, 871]

Sulfides — cadmium sulfoselenides (red and orange), cadmium sulfide (orange), cadmium/zinc sulfides (green to yellow), zinc sulfide (white), and ultramarines (blue and violet) — are generally thermally and light stable and migration and alkali resistant but are sensitive to acids. Cadmium compounds have a moderately high cost, and toxicity may be a problem due to the heavy metal content. Compounds with low or no selenium content are less resistant to weathering, since they can easily oxidize to sulfates. [826, 825]

Ultramarines are sulfide-silicate complexes containing sodium and aluminum. They are transparent pigments with weak tinting strength (a measure of brightness) and are widely used in polypropylene and high density polyethylene. Ultramarine blue pigments are highly acid-sensitive and can fade in the presence of acidic catalyst residues. They exhibit poor UV stability; calcium carbonate (CaCO_3)-filled grades have shown greater UV stability than talc-filled grades, due to the higher absorption capacity of talc and to the

greater amount of heavy metal residues (Fe, Cu, Mn), which catalyze oxidation. Addition of UV stabilizers increases the UV resistance of ultramarine blue; however, it is not usually recommended for outdoor applications of filled polypropylene. [826, 825, 838]

Oxides of iron, barium, titanium, antimony, nickel, chromium, lead, and combinations of two or more metals are used in pigments. They have high thermal stability if the metal is present in its highest oxidation state (i.e. Fe^{+3} in Fe_2O_3 ; iron oxide red), but oxidation can occur if the metal is present in a lower oxidation state (i.e. Fe^{+2} in $(\text{FeO})_x \cdot (\text{Fe}_2\text{O}_3)_y$; iron oxide brown — oxidation from Fe^{2+} to Fe^{3+}). Iron oxide colors used in plastics are mainly red and brown; colors produced are relatively dull. They have excellent hiding power (a measure of opacity produced in the resin) and good alkali and light resistance. They are easy to disperse but require careful processing at high temperatures. Chromium oxides produce dull green colors with moderate opacity and low tinting strength. They are light and chemically resistant and have high thermal stability if not hydrated. [859, 826]

Titanium dioxide (TiO_2) is a widely used white pigment that exhibits excellent brightness and opacity and good thermal stability. It represents >90% of the inorganic pigments used in plastics coloration and over 65% of all colorants used in the plastics industry. Titanium dioxides can accelerate surface photooxidation of the plastic if not surface-treated; the anatase form of TiO_2 has a greater effect. Anatase is not as widely used as the rutile form, which also has better hiding power. Anatase is used when a bluer white, lower abrasiveness, or controlled chaulking is required. [825, 859]

Lead chromates are yellow, bright pigments with very good migration resistance, moderate tint strength, and temperature stability to 180°C (354°F). They are alkali-sensitive and, if not treated, darken when exposed to light. Molybdate orange, a combination of lead chromate, lead sulfite, and lead molybdate, is an orange pigment with good light stability and acid resistance but poor alkali resistance. It can be combined with other pigments to make a red shade. [826]

Iron blues, based on ferric ammonium ferrocyanide, and chrome greens, a combination of iron blues, lead chromate, and lead sulfate, are not generally used in polypropylene. Chrome greens are

primarily used in low density polyethylene garbage bags and iron blues in low cost applications. [826]

3.7.4 Organic pigments

Organic pigments are usually brighter, stronger, and more transparent than inorganic pigments but are not as light-resistant. They can be partially soluble in plastic, with a greater tendency to migrate. Azo pigments are the largest group of organic pigments; they contain one or more azo ($-\text{N}=\text{N}-$) chromophoric groups and form yellow, orange, and red pigments. Monoazo pigments, with only one chromophore, exhibit low thermal and light stability and have a tendency to bleed; they are not usually used in plastics. Polyazos, with more than one chromophore, do not tend to bleed and have better thermal stability and excellent chemical resistance. Polypazos include disazo pigments; higher molecular weight disazo condensation products, with brighter colors and thermal and light stability; dianisidine orange, with a brilliant color but poor light stability; and pyrazolone pigments, with good thermal stability and migration resistance and good light stability in red pigments. Metallized azos are prepared by precipitating from a metal salt or laking onto an absorptive surface. These red-maroon pigments have poor to good thermal stability, fair to good light stability, and good migration resistance. They include Lake Red C, Permanent Red 2B, Nickel azo yellow, Lithol Red, and Pigment Scarlet. [871, 820, 826]

Nonazo pigments have varied structures, usually polycyclic and sometimes complexed with metals. Phthalocyanine blues and greens, most of which form complexes with copper, are highly stable to light, heat, and chemicals; they form highly transparent, intense colors with high tinting strength. Quinacridones (red, violet, orange) exhibit good light stability and excellent bleed and chemical resistance, but they are expensive and are best suited for plastics such as polystyrene and acrylic due to low thermal stability. Dioxazines (violet) are strong, high cost pigments with excellent light stability and limited heat stability. They are used in tinting other pigments and in low temperature applications in acrylic sheet, polyethylene and polyvinyl chloride. Isoindolinones (yellow, orange, red) are applicable to all plastics but are primarily used in automotive applications due to their high cost. Other nonazo pigments include perylenes, flavanthrones, and anthraquinones. [859, 826]

Carbon blacks are the most widely used black pigment. They are formed from incomplete combustion of natural gas (channel blacks) or by reduction of liquid hydrocarbons in refractory chambers (furnace blacks). They are composed of different functional groups (carboxyl, phenol, lactone, etc.) which increase dispersibility, and different particle sizes; finer particle sizes result in deeper shades. Carbon blacks have some of the smallest particle sizes and highest surface areas of all pigments; furnace black particles are larger than those of channel blacks. Carbon blacks have high strength, but loose forms can cause severe dusting. [826, 859]

3.7.5 Special effect pigments.

Some colorants produce special effects in the plastic, such as pearlescence or phosphorescence. The pigment must be well dispersed in the resin and must be carefully handled during processing. These pigments are most effective on transparent plastics; mechanical abuse and the presence of opaque fillers or pigments can reduce the effect desired. [826]

A “granite” appearance is produced by adding a foreground color, such as colored mica flakes (500–2000 μm) or large glitter flakes (≥ 6.4 mm; ≥ 0.25 in.) to a background color. Pearlescent pigments produce pearly lusters and iridescence — the resin has a soft, silky and/or multicolor appearance. Luster is produced by reflection of light by thin (< 1 μm) platelets oriented in parallel layers. Length of the platelets is 10–40 μm . Any scattering of light by the plastic or other pigments will reduce the platelet reflection and the pearlescence. Pearlescent pigments must be inert. Due to the orientation of the platelets, the appearance of the material can change with the angle of viewing. Pearlescent pigments include titanium dioxide-coated mica (muscovite), ferric oxide-coated mica, and bismuth oxychloride. The coatings vary in concentration from 10–60%; mica also provides mechanical support. Coated mica can resist several years of outdoor exposure. [872, 826]

Metallic flakes are used to produce silvery lusters or gold bronze effects. Aluminum, copper and alloys of copper and zinc (bronze) are commonly used. Flake particles are < 1 μm in thickness and < 50 μm in length; smaller particles produce greater opacity and a metallic sheen, while larger particles result in more brilliance and glitter. Aluminum can be processed up to 310–340°C

(600–650°F), with loadings from 0.5–4%. It is usually treated to resist oxidation. Copper is susceptible to oxidation beginning at $\sim 120^\circ\text{C}$ (250°F) and can tarnish, depending on the temperature and duration of exposure. Slow discoloration occurs in outdoor applications. [826, 872]

Fluorescent pigments appear to glow in daylight; they absorb visible and ultraviolet light, then emit the light at longer wavelengths. A glow appears when this light combines with the reflected color of the plastic. Phosphorescent pigments also emit light at longer wavelengths than it was absorbed, but the yellow-green glow appears only in darkness. Phosphorescence is produced by the addition of doped zinc sulfide. [826, 872]

3.7.6 Colorant forms

Colorant forms include dry color, color or pellet concentrates, liquid color, and precolored resin. A precolored resin contains the color already dispersed in the resin; all other forms require dispersion by the resin processor. The colorant form selected is dependent on factors such as volume requirements, handling provisions, regulatory concerns, labor and inventory costs, and equipment, in addition to performance requirements such as color strength development, color-matching tolerances, and color consistency in long runs. [826]

Dry colorants are powders composed of one or more pigments or dyes. They are supplied in preweighed packets and must be compounded and dispersed into the resin. Dry pigments are usually dispersed in polypropylene by batch blending; addition of wetting agents helps the pigment adhere to the resin surface. Careful attention is required for consistent color from batch to batch, and accurate weighing and blending are necessary for long-term, uniform color. Dry colorants are most often used for short runs, emergency situations, and the rotational molding of polyethylene. Dry colorants can be dusty and dirty during handling. Anti-dusting agents are available from suppliers, as well as closed packaging systems that hook up to pneumatic conveying equipment. [871, 821, 642]

Dry colorants are the most economical colorants. They provide the largest selection of colors and use a minimum of warehouse space. They are difficult to disperse, however, and dusting and cross-contamination problems discourage their use. Higher costs may result from problems with clean-up, color changes, scrap generation, and OSHA regulations concerning dust. [871, 826]

Color concentrates are colorants dispersed in a resin carrier that is formulated for use with a particular polymer family. In order to obtain a melt flow similar to that of the polymer, the carrier resin frequently has a lower melt flow than the polymer in order to compensate for the effects of pigments on melt flow. Low density polyethylene is frequently used as a carrier; however, for demanding applications, polypropylene should be used to insure optimum processing and compatibility. The form of the color concentrate can be matched to that of the polymer to be colored and includes pellets, beads, cubes, wafers, microbeads, and chips. [821, 826, 642]

Color concentrates can contain 10–80% colorant, depending on the application requirements, the pigment used, and the compounding equipment, and are added to the polymer at a level of 1–10%. Concentrates can be blended either by batch blending or by automatic metering at the processing equipment. Letdown ratios of 100:1 to 10:1 (polymer matrix:color concentrate) can be accurately metered with modern equipment, and other additives can be incorporated during pigment compounding. [821, 826]

Color concentrates are the most popular form of colorant for in-house coloring. They are dust-free, easy flowing, and easy to meter. They require little warehouse space, and color changes are relatively easy. Newer concentrates include those designed for specific applications, such as injection-molded polypropylene battery cases, and concentrates that can be used in a wide variety of polymers, simplifying inventory for plastics processors. [826, 821]

Liquid color is composed of a pigment in a non-volatile liquid carrier. Liquid carriers include mineral oils and complex fatty acid derivatives and can contain surfactants for easier dispersibility and clean-up. A range of viscosities are available, from maple syrup to gel-like consistencies, and good

dispersion can frequently be obtained with high pigment loadings (10–80%); higher loadings are possible with liquid color than with color concentrates. High pigment loadings can result in letdown ratios of greater than 100:1. Usually the highest loading possible is used, both for economy and to minimize the amount of carrier added to the matrix polymer. The carrier can affect polymer properties and can lubricate the polymer, affecting process cycling and back pressure in injection molding. [821, 826]

Liquid colorants are compatible with many plastics; however, they require special metering equipment and are most cost-effective for long runs. They are used in injection molding and extrusion and are usually pumped in below the hopper at the throat. Consistent color levels can be obtained by electronically matching the metering speed of the pump with that of the extruder. Extreme hot or cold temperatures can cause adverse effects on the liquid colorant, and spills and disposal of used containers may be costly. Other additives can be added to the liquid concentrate to tailor it for a specific application. [826, 821, 642]

In precolored resins, the colorant is already compounded into the polymer, and no additional compounding is necessary before processing. Precolored resin can be in the form of pellets, beads, or fine powder. The best dispersion is usually obtained with precolored resins; as little as 0.25–2 weight % pigment is necessary for non-filled polymers. Precolored resins are more expensive, however, and require more warehouse space than other forms of colorant. They are useful for hard-to-color materials such as highly-filled plastics, engineering plastics, and polymers with a high inherent color. [871, 821, 825]

Advantages and disadvantages of the various forms of colorant are compared in Table 3.1. [642]

Table 3.1 Comparison of Coloring Techniques

LEGEND: 1-Highest 2-Medium 3-Lowest

Factor	Color Concentrate	Liquid Colorant	Dry Pigment	Precolored Resin
Cost	1	2	3	1
Dispersion Characteristics	1–2	1–2	3	1
Ease of Handling	2	1	3	1
Inventory Required	1	2	3	1
Difficulty of Matching Color	2	3	1	3
Ease of Color Change	2	1	3	1–2

3.8 Antistatic agents

Polypropylene is an insulator; because it does not conduct electricity, a static charge can build up on the surface of a part, leading to problems with dust accumulation, static cling in films and fabrics, electric discharges that can produce shocks or fires, and damage to electronic components. Polypropylene and other polymers used in computer rooms (furnishing, fixtures, flooring) and in the handling and packaging of microelectronic chips require protection against electrostatic discharges. [870]

3.8.1 Electrostatic charges

Static electricity or an electrostatic charge is a deficiency or excess of electrons which occurs on ungrounded or insulating surfaces. It is produced by triboelectric charges, charges that are generated by friction between two surfaces, such as the movement of paper through a copier or printer. The ability of a material to discharge static electricity is classified according to its surface resistivity, the ratio of DC voltage to current passing across a square unit of area, in ohms/sq. (Table 3.2) Surface resistivity is independent of the size of the square or its units.

A material with useful antistatic properties has a surface resistivity between 10^9 and 10^{12} ohms/square. Static decay testing measures the ability of a grounded material to dissipate a charge induced on its surface. The decay rate of insulating polymers is much slower than those treated with electrically dissipative materials (Figure 3.16). [870, 698]

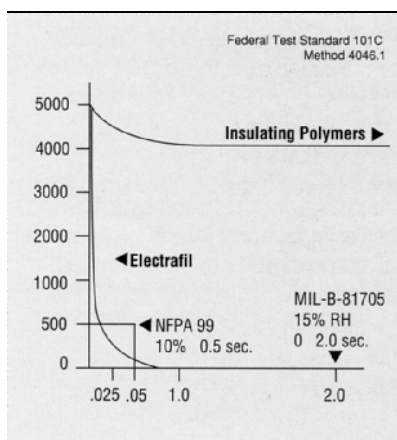


Figure 3.16 The static decay rate of an insulating polymer and a polymer containing a conductive filler (Electrafil; DSM Engineering Plastics). Static decay testing is performed according to methods such as the Federal Test Standard 101C; antistatic formulations must meet military or industrial standards such as MIL-B-81705 (decay to 0% of initial charge in ≤ 2 s) or NFPA 99 (decay to 10% of initial charge in 0.5 s). [698]

3.8.2 Types of antistatic agents

Antistatic agents, commonly called antistats, can be ionic or nonionic. Ionic antistats include cationic compounds, such as quaternary ammonium, phosphonium, or sulfonium salts, and anionic compounds, usually sodium salts of sulfonates, phosphates, and carboxylic acids. Nonionic antistatic agents include esters, such as glycerol esters of fatty acids, and ethoxylated tertiary amines. Many are FDA-approved. Nonionic antistats are commonly used in polyolefins; glyceryl monostearate is used in many polypropylene injection molding applications, at levels ranging from 0.5 to $>1\%$. Loading levels depend on resin processing temperatures, the presence of other additives, and application requirements such as clarity, printability, and FDA compliance. [862, 861, 822, 824]

Antistat molecules are generally both hydrophilic and a hydrophobic; the hydrophobic portion is compatible with the polymer, while the hydrophilic portion extends onto the surface and attracts water molecules from the air. A thin film of moisture forms along the surface, which increases the surface conductivity. Electrons are transferred out into the air, and the potential difference producing the static electricity is eliminated. Ionic antistats also function by conducting electrons through ions present at the plastic surface. [824, 822].

Antistatic agents can be internal or external. Internal antistats are compounded into the polymer. They have limited compatibility with the polymer and continually migrate to the polymer surface, forming a thin film that does not alter the surface appearance. The antistat must exhibit the proper level of compatibility with the particular polymer for a controlled migration to the surface. [820, 822, 862, 870]

External antistats are applied directly to the plastic surface after processing, usually from an aqueous and/or alcoholic solution (1–2%) as a spray or dip. External antistats can be easily removed by contact with solvents or by rubbing or wiping. They are used primarily in textile fibers, cosmetic packaging, medicine bottles, and household cleaner bottles to eliminate dust pickup dur-

Table 3.2 Classifications of Surface Resistivity

Surface Resistivity (ohms / sq)	Classification
$\leq 10^5$	Conductive
$> 10^5$ to $\leq 10^9$	Static Dissipative
$> 10^9$ to $\leq 10^{14}$	Antistatic
$> 10^{14}$	Insulative

ing shipping and handling. Internal and external antistatic agents can also function as lubricants and mold release agents; lubricants can reduce surface friction and the resultant triboelectric charging. [820, 822, 862, 870]

3.8.3 Electrically conductive materials

Static electricity can also be dissipated by addition of a conductive filler, such as carbon black. Electrons are then conducted through the polymer. High conductivities are possible — surface resistivities of 10^2 — 10^3 ohms/sq can be obtained with high loadings. Applications include printer brackets, trays, and bushings. [698]

3.9 Slip agents

Slip agents are used in polypropylene films and sheets to provide surface lubrication during and immediately after processing. They have limited compatibility with the polymer and exude to the surface, providing a coating that reduces the coefficient of friction. Slip agents reduce sticking of the plastic to itself by minimizing tack and facilitate processing on high-speed packaging equipment. They also can improve antistatic properties, lower plasticity, and act as mold release agents. [877, 870]

Slip agents are usually modified fatty acid esters, used in concentrations of 1–3 parts per hundred (phr) or fatty amides, especially erucamide and oleamide. Erucamide is commonly used in polypropylene. Erucamide exhibits slower blooming than oleamide and is more resistant to high processing temperatures. Both have FDA acceptance for a wide variety of applications [822, 825, 877]

Slip agents can also provide antifog properties in food packaging. Fogging occurs when water droplets, formed from exposure of the moisture in foods to low storage temperatures, condense on the inside surfaces of packaging films. Fatty acid esters form a continuous film on the interior film surface, maintaining the clarity of the packaging. [877]

3.10 Antiblocking agents

Antiblocking agents prevent plastic films from sticking together due to cold flow or a buildup of static electricity. They can be applied externally or internally. When incorporated internally, they must be partially incompatible with the polymer so that they can exude to the surface. Antiblocking agents include natural and manufactured waxes, metallic

salts of fatty acids, silica compounds, or polymers such as polyvinyl alcohol, polyamides, polyethylene, polysiloxanes, and fluoroplastics. [822, 877]

3.11 Lubricants.

Lubricants are used in plastics processing to lower melt viscosity or to prevent the polymer from sticking to metal surfaces. Internal lubricants act intermolecularly, making it easier for polymer chains to slip past one another. They reduce melt viscosity and provide better polymer flow. External lubricants act at the molten polymer surface, between the polymer and the processing equipment. Materials used for lubricants include metal soaps, hydrocarbon waxes, polyethylenes, amide waxes, fatty acids, fatty alcohols, and esters. [825, 876, 822]

Polyolefins are more easily processed than other polymers and generally require little, if any, lubricants. Calcium stearates are used for internal lubrication in polyolefins, to alter melt viscosity, promote fusion, and increase internal shear. They also can function as external lubricants, depending on the formulation and processing temperatures. Zinc stearates are also used as processing lubricants. Polyethylene waxes provide improved melt flow in some polyolefins and are also used as mold release agents. Low molecular weight waxes function primarily as internal lubricants; molecules with branching and higher molecular weights provide external lubrication. The optimum molecular weight for a particular application depends on the lubrication desired, processing conditions, and formulation. [876, 88, 822]

3.12 Blowing or foaming agents

Blowing agents, or foaming agents, are liquids or solids that form a gas during polymer processing. The gas forms minute cells or bubbles within the polymer, resulting in a foamed or porous structure. The foaming process is affected by the type of blowing agent used, the gas and its solubility in the polymer, the compounding method, processing temperatures and pressures, and the melt viscosity and crystallinity of the polymer. [822, 901, 819, 821]

Foaming agents are used to decrease the density of a polymer — density reductions of about 50–60% can be achieved with loading levels of about 0.5–2.5% by weight — and to reduce material costs. Finishing costs are higher in foamed polymers, however, due to the necessity of paint-

ing or covering the foamed material. Foamed plastics have improved electrical and thermal insulative properties and higher strength-to-weight ratios; however, mechanical properties such as stiffness, tensile strength, and compressive strength are decreased due to a lower amount of plastic material in the foam compared to the solid. [819, 821]

The amount of blowing agent used affects the properties of the foamed plastic, and different amounts are used for particular applications: 0.1% for elimination of sink marks in injection molded parts, 0.2–0.8% for production of injection molded structural forms, 0.3% for extruded foamed profiles, 1–15% for formation of vinyl foams, and 5–15% for compression-molded foam products. Nucleating and cell-sizing agents can be added to produce cells of a more uniform size and to enhance the symmetrical expansion of cells during the foaming process. [822, 819, 821]

Blowing agents can be classified as physical or chemical, depending on how the gas is generated. Physical blowing agents undergo a change of state during processing, while chemical blowing agents, usually solids, undergo a decomposition reaction during polymer processing that results in formation of a gas. [819]

3.12.1 Physical blowing agents

Physical blowing agents are compressed gases or volatile liquids. Compressed gases, usually nitrogen, are injected under high pressure into the polymer melt; as the pressure is relieved, the gas becomes less soluble in the polymer melt and expands to form cells. Nitrogen is inert, nonflammable, and can be used at any processing temperature. No residue is left in the foamed plastic, so that recycling of the plastic part is easier. The use of compressed nitrogen, however, generally produces foams with a coarser cell structure and poorer surface appearance than nitrogen produced with chemical blowing agents, although nucleating agents can be added for a finer cell structure. [819, 822, 901]

Liquid physical blowing agents are volatile and change from a liquid to a gaseous state when heated to polymer processing temperatures. They are short-chain chlorinated and fluorinated aliphatic hydrocarbons (CFCs). Although they can be used over a wide temperature range and at low (atmospheric) pressures, they have been discontinued in most formulations due to their role in the reduction of stratospheric ozone. [822, 819]

3.12.2 Chemical blowing agents

Chemical blowing agents decompose at processing temperatures to form a gas. The most important criterion for selection of a chemical blowing agent is that the decomposition temperature match the processing temperature of the polymer; little or no foaming will occur at processing temperatures below the decomposition temperature, while processing temperatures that are too high can result in overblown or ruptured cells and poor surface quality. Activators (“kickers”), including alcohols, glycols, antioxidants, and metal salts, can be added to lower the decomposition temperature. Other selection considerations include the type and amount of gas liberated and its effect on the final product. [822, 819]

Chemical blowing agents (CBAs) can be classified as inorganic or organic, and the decomposition can be endothermic or exothermic. Endothermic blowing agents, usually inorganic, require the input of energy for the decomposition reaction to take place, while exothermic blowing agents, usually organic, release energy during decomposition. Exothermic chemical blowing agents commonly have a higher gas yield than endothermic CBAs, while the lower gas yield and pressure associated with endothermic CBAs produce foams with a smaller cell structure, resulting in improved appearance and physical property performance. Endothermic and exothermic CBAs have recently been combined in a single product, in which the exothermic CBA provides the gas volume and pressure necessary for lower densities, and the endothermic CBA produces a fine, uniform cell structure. [824, 821]

3.12.2.1 Inorganic chemical blowing agents

Typical inorganic blowing agents are sodium bicarbonate, sodium borohydride, polycarbonic acid, and citric acid, which evolve primarily carbon dioxide gas upon decomposition. Sodium bicarbonate is the most common inorganic blowing agent. It is inexpensive, and it decomposes endothermically at a low temperature, over a broad temperature range (100–140°C; 212–284°F). At temperatures $\geq 142^\circ\text{C}$ (287°F), decomposition becomes more rapid, facilitating its use in polyolefins. Its decomposition is less controllable than organic blowing agents, however, and it can form an open-celled foam structure. Its gas yield is 267 cc/g. Polycarbonic acid decomposes at about 160°C (287°F), with a gas yield of about 100 cc/g. It is

also used as a nucleating agent in physical blowing agents. [822, 819]

3.12.2.2 Organic chemical blowing agents

Organic blowing agents evolve gas over a specific, narrow temperature range and are selected according to the processing temperature of the polymer. The most common low temperature blowing agent is 4,4'-oxybis(benzenesulfonyl hydrazide) (OBSh), with a decomposition temperature of 157–160°C (315–320°F) and gas yield of 125 cc/g. High temperature blowing agents, with decomposition temperatures of greater than about 230°C (450°F), include 5-phenyltetrazole, with a decomposition temperature of 240–250°C (460–480°F) and trihydrazine triazine (THT). [822, 824, 819]

Azodicarbonamide (ABFA), with a decomposition temperature of 204–213°C (400–415°F) is commonly used in polypropylene (melting temperature ~168°C; 334°F). The use of activators can reduce the decomposition temperature to 150°C (300°F). ABFA is a yellow powder that decomposes exothermically, with a gas yield of about 220 cc/g, to produce a gas mixture containing 65% nitrogen. ABFA produces a fine, uniform cell structure but can produce discoloration in the foamed part. It is nontoxic and is FDA-approved for a wide variety of applications, including those involving food contact. The high gas yield, good performance, and low cost (\$1.80–\$2.00/lb in US dollars) of ABFA make it the most widely used foaming agent. [822, 819, 821]

The average particle size of ABFA ranges from 2–20 µm; fine particle sizes decompose at lower temperatures than coarser particles. Particle size has a large effect on the final cell structure in low pressure applications; however in high pressure processing such as injection molding or extrusion, the effect of particle size is less critical. The effect of activators is also dependent on ABFA particle size; fine particles are more easily activated than coarse particles. [819]

p-Toluenesulfonyl semicarbazide (TSSC) is also used in polypropylene, although it decomposes at an intermediate-to-high temperature (228–236°C; 442–456°F). Activators can be used to decrease the decomposition temperature. It has a gas yield of about 140 cc/g; the gas mixture consists of nitrogen, carbon monoxide, carbon dioxide, and trace amounts of ammonia. Its white color and nonstaining residue are important in applications requiring color quality. It is flammable and burns rapidly when ignited, producing a large amount of residue. [822, 819, 824]

3.12.3 Available forms of blowing agents

Chemical foaming agents are available as dry powders, liquid dispersions, and pellet concentrates. They can be incorporated by dry-blending with the resin powder, tumble-blended with resin pellets, blended using a hopper blender, metered in at the feed throat, or pumped into the barrel. [822, 821]

4 Fillers and reinforcements

Fillers and reinforcements are added to polypropylene in order to reduce costs or enhance mechanical properties. Extenders are inexpensive fillers that are added primarily to increase bulk, reducing the amount of the more expensive polymer required for the application, although they can increase stiffness and heat resistance. Reinforcing fillers provide a substantial improvement in mechanical properties, such as tensile strength, heat distortion temperature, and modulus of elasticity. Reinforcements include fibers, mica, and wollastonite; the use of glass fibers in polypropylene has greatly increased its use as a substitute for more expensive engineering plastics. Fillers and reinforcements commonly used in polypropylene are calcium carbonate, talc, mica, barite, glass spheres, and carbon and glass fibers. Maximum concentrations are usually 50%, although higher loadings are also used. [853, 866, 849, 697]

4.1 Characteristics of fillers

Some reinforcing fillers function by forming chemical bonds with the polymer. Others produce enhancements in mechanical properties by taking up volume; they bind to nearby polymer chains, decreasing the chain mobility and increasing polymer orientation at the filler surface. The increased orientation results in increased stiffness, lower deformability, and increased strength. Reduced mobility results in higher glass transition temperatures in filled polymers, intensifying the inherent brittleness in polypropylene at temperatures below 0°C (32°F); as a result, many reinforced polypropylene resins are based on copolymers. A uniform dispersion of filler in the polymer matrix increases the polymer – filler interaction, so that greater amounts of the polymer are oriented. [860]

The effect of a filler on resin properties is dependent on the aspect ratio (ratio of major to minor dimension of a particle or length:diameter) and size of the particle, the particle size distribution of the filler, filler surface treatment, and the dispersion of filler in the polymer. High levels of reinforcement can be obtained from fibers made from electrical glass (E glass, made from Pyrex) due to their high aspect ratio, and the plate or flake-like particles of talc or mica provide more reinforcement than the more spherical calcium carbonate

particles or glass spheres. The larger surface areas of smaller particles provide better adhesion to the polymer, and the amounts of coarse and fine particles influence particle packing during compounding and the optical properties of the resin. The size, shape, and type of filler affect dispersion, in addition to interactions between resin and filler, resin flow properties, filler surface treatment, machine geometry, and processing parameters. Ultimate filler particle size and spatial uniformity of the filler in the resin is dependent on the degree of dispersion. [662, 847, 849, 880, 860]

Abrasion during processing can result in equipment damage. Abrasivity of a filler is dependent on the amount of coarse filler particles and the Mohs hardness value; abrasion can be minimized by selection of fillers with a 325 mesh particle size. Mohs hardness values are lower for talc, kaolin, and calcium carbonate than for the harder fillers such as wollastonite, silicas, and feldspar. [866]

Chemical reactions of the filler or impurities can have a negative effect on resin properties. The alkaline surface (pH 9.5) of calcium carbonate particles results in low acid resistance to even weak organic acids and increases the potential for thermal oxidation of the resin. The likelihood of polymer oxidation is increased by mineral fillers with high surface areas, high pH values, high moisture levels, and a high content of reactive iron oxides. [860, 942]

Due to its nonpolar chemical structure, polypropylene interacts poorly with the typically polar filler materials, and optimum dispersion is difficult to achieve. Coupling agents, usually silanes and titanates, are frequently used to improve the interfacial bond between filler and resin and to further enhance mechanical properties. Coupling agents are bifunctional molecules, in which one end reacts with polar, inorganic materials, while the other end reacts with organic, nonpolar substrates. They function as molecular bridges between filler and resin. Titanates are hydrophobic organotitanium compounds compatible with polypropylene that react with free protons on the filler surface. Silanes are organo-silicon compounds that bind to hydroxyl (OH) functional groups on the filler surface. Many coupling agents are available commercially, with different functional groups ap-

propriate for the particular resin. Newer polymeric coupling agents composed of maleic anhydride grafted onto polypropylene are also available. They exhibit improved physical properties at lower loadings than silanates and titanates. [702, 852, 846, 847]

Coupling agents are used to improve adhesion in glass- and mineral-filled polypropylene. Micrographs of glass fiber-filled polypropylene with and without addition of coupling agents are shown in Figure 4.1. The improved adhesion obtained with coupling agents results in enhanced mechanical properties, such as tensile strength, flexural modulus, impact strength, and heat deflection temperature, and lower melt viscosities than in the unfilled polymer. The effect of coupling agents on tensile strength, flexural modulus, and heat deflection temperature is shown in Figure 4.2. [819, 697, 459]

4.2 Calcium carbonate

Calcium carbonates are one of the most abundant minerals in the earth’s crust. They occur in the form of limestone and chalk, formed from fossils, and marble, formed from the metamorphosis of sedimentary rock. They consist mostly (>98%) of calcium carbonate (CaCO_3), with trace amounts of magnesium carbonate, iron oxide, and aluminum silicates. Dolomite is a blend of calcium and magnesium formed by metamorphosis. All are relatively soft minerals (Mohs hardness of 3), white in color, with a specific gravity of 2.71 at 23°C (73°C). Physical properties of calcium carbonate,

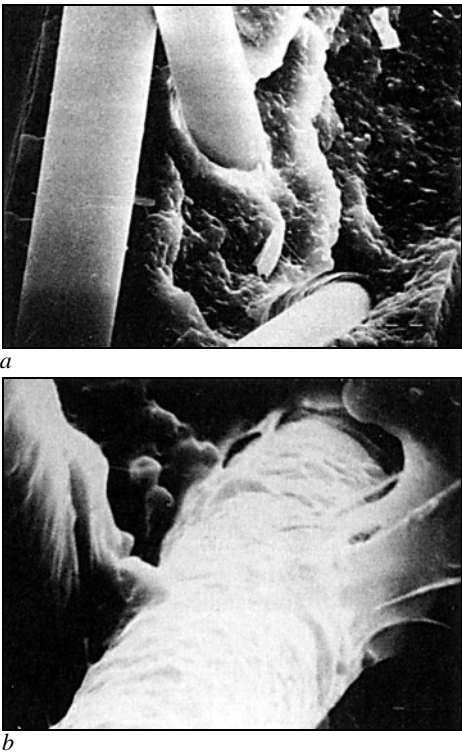


Figure 4.1 Glass fiber-filled polypropylene. a) No coupling agent is present; resin does not adhere to the fibers. b) With the addition of a coupling agent, the resin coats and adheres to the fibers. [697]

talc, mica, and barite are given in Table 4.1. A photomicrograph of calcium carbonate particles is shown in Figure 4.3. [854, 860, 828, 827, 942]

Calcium carbonate is the most widely used filler for plastics. It is inexpensive and can be used at high loadings. It is generally used as an extender; however, it can improve stiffness and im-

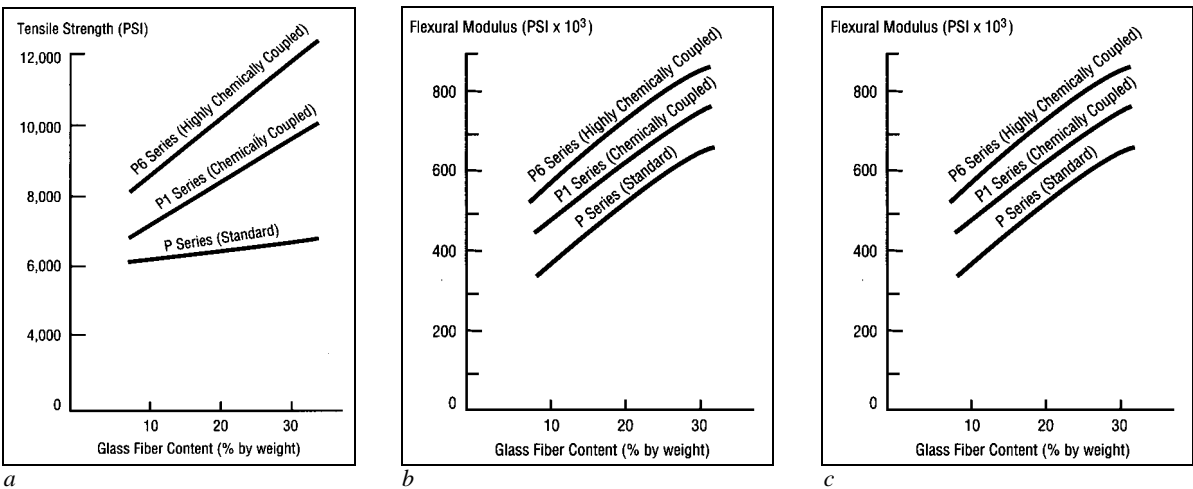


Figure 4.2 Effect of coupling on tensile strength, flexural modulus, and heat deflection temperatures of glass fiber-reinforced polypropylene. a) tensile strength vs. glass fiber content b) flexural modulus vs. glass fiber content c) heat deflection temperature vs. glass fiber content. Tensile strengths, flexural moduli, and heat deflection temperatures all increase with increasing glass fiber content and with increased coupling. P, P1, and P6 Series polypropylene are from Thermofil Engineering Thermoplastics. [459]

pact strength, especially with fine particle grades. The flexural modulus of a 40% calcium carbonate-filled polypropylene homopolymer is about 3000 MPa (400,000 psi), midway between unfilled and talc-filled resins. Calcium carbonates provide high brightness and high gloss. Limestone- and marble-based products are generally used when aesthetic considerations are important; the amount of the more expensive titanium dioxide pigment in a formulation can be reduced by up to 50%, with equivalent whiteness, by substitution of calcium carbonate. Disadvantages include lowered tensile strength and compressive strength, greatly reduced elongation, and low resistance to organic acids. [847, 159, 697, 849, 866, 851, 827]

Calcium carbonates are available in different grades: dry processed, wet or water ground, beneficiated ground, precipitated, and surface-treated. Precipitated is a synthetic form produced by carbonization and is available in very fine particle sizes (0.7–2.0 μm). Surface treated grades are coated with lipophilic substances such as stearic acid or calcium stearate to improve dispersibility, increase oxidation resistance of the filled resin, and reduce wear on processing machinery. In experimental studies, coated calcium carbonates resulted in higher values for impact strength and elongation at break and enhanced whiteness compared to uncoated grades. In beneficiated ground, the most widely used grade, iron and silica are removed to minimize resin degradation, and the mineral is finely ground, with median particle sizes of 1–10 μm . The largest particle size (>12 μm) is obtained with dry processed grades; coarse particles are removed in wet ground grades, with a median particle size of <3 μm . [827, 866, 854, 942]

4.3 Barite

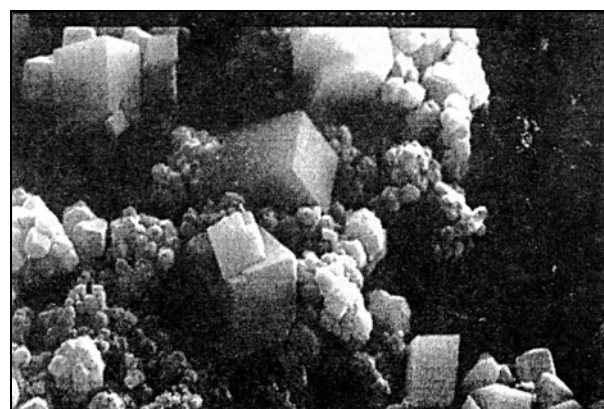
Barium sulfate (Figure 4.3), commonly called barite, is found in the hydrothermal veins of cavity fissures in limestones, sandstone, shales, or clays or as surface deposits resulting from limestone weathering. Barite brightness depends on origin; brown buff barite (brightness 80–85) is found in Nevada, Missouri, Georgia, Illinois, and Mexico, while pigment grade white barite (brightness 92–94) is obtained almost exclusively from China. [942]

Barites are the most chemically resistant of the commonly used minerals in polypropylene (calcium carbonate, talc, mica, and barite; Table 4.1), with excellent resistance to acids, alkali, and all known

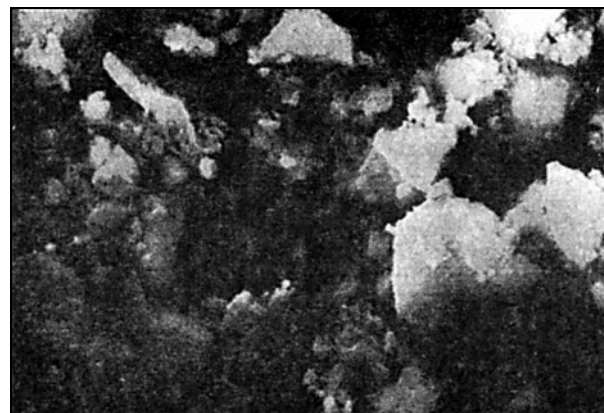
organic solvents. Due to a 60% higher specific gravity, loadings are low compared to other mineral fillers, and the effect on physical properties of the filled resin is not as pronounced. Barite has a high refractive index than other minerals. It is used in heavier parts or for applications that require sound deadening or corrosion resistance. [942]

4.4 Talc

Talc is a hydrated magnesium silicate ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$), with small, varying amounts of aluminum, iron, and calcium oxides, depending on the mining site. It is soft (Mohs hardness of 1.0), with low abrasion and a slippery texture, and it is highly oleophilic. The form used commercially is plate-like (Figure 4.4), with an aspect ratio of 15–20. It is inexpensive and, although it was originally used as an extender, it is now considered a reinforcing filler due to its high aspect ratio. Particle sizes range from 2 μm to greater than 45 μm ; optimum aspect ratios are obtained with talc particles finer than 325 mesh (particle size smaller than 45 μm). Specific gravity ranges from 2.7 to 2.8. Its sandwich-like structure of magnesium oxide and hy-



a



b

Figure 4.3 Micrographs of spherically shaped mineral fillers. a) calcium carbonate b) barite [942]

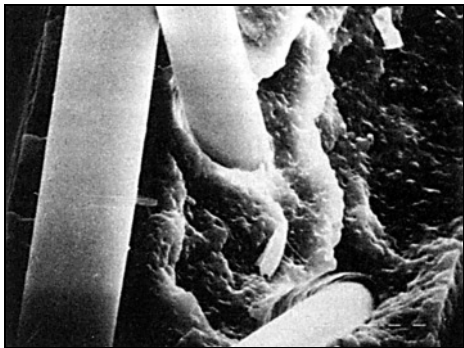


Figure 4.4 Micrograph of Chinese talc particles. Chinese talc is most often used in polyolefins due to higher purity and superior color and properties than talcs from other areas such as Montana, Vermont, Texas, or Canada. [942]

dioxide between layers of silicon dioxide provides inertness to most chemical reagents and acids, and it is heat stable up to ~900°C (1650°F) and unaffected by processing conditions. Talc is a nonconductor of electricity and exhibits low thermal conductivity and high resistance to heat shock. [847, 866, 827, 767, 942]

Talc is widely used in polypropylene, at loadings of ~10–40%. Talc-filled resins exhibit increased stiffness, heat resistance, and high temperature creep resistance, better dimensional stability, and heat and moisture resistance. Tensile strength is unaffected. Impact strength can decrease dramatically, especially in copolymers; however, fine particle sizes can improve impact strength. Living hinge properties are also reduced.

The resin color of talc-filled polypropylene can vary from white to tan, depending on the origin of the talc; the presence of iron hydroxides (limonite) imparts a yellowish cast to talc particles. All commercial grades of talc are dry ground. Physical properties of talc are given in Table 4.1. [697, 827, 847, 866, 942]

4.5 Mica

Mica is an aluminosilicate reinforcing filler obtained from the minerals muscovite ($\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$), phlogopite ($\text{KMg}_3(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$), or biotite ($\text{K}(\text{Mg}, \text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$). Phlogopite and biotite form a continuous series in which some of the magnesium (Mg) is replaced by iron (Fe); micas can contain up to 5% iron. Biotite, with the highest iron content, is black, while phlogopites can be golden brown or almost black in color. Muscovites contain the lowest amounts of iron and are light-colored. The iron in mica is in an unreactive form and does not increase the rate of polypropylene oxidation. [942, 955]

The plate-like form of mica (Figure 4.5) provides reinforcement in a plane, in contrast to fibers, which reinforce in only one direction. Mica flakes have aspect ratios ranging from 10 to 150, with particle sizes from 45–500 μm (325 to 40 mesh); flake thickness can be as low as 0.1 μm , depending on the degree of delamination. Good aspect ratios for optimum reinforcement can be obtained at mesh sizes

Table 4.1 Physical Properties of Commonly Used Minerals

Property	Barite	Talc	Calcium Carbonate	Mica (phlogopite)
Particle shape	Orthorhombic	Platy	Orthorhombic	Platy
Specific gravity	4.5	2.8	2.7	2.8
Chemical resistance Acids Alkali	Excellent Excellent	Good Good	Poor Fair	Good Good
Thermal stability (°C)	1580	900	680	1500
pH (10% solution)	6.5–7	9	9–9.5	9–9.5
Hardness (Mohs scale)	2.5	1	3	2.5
Thermal conductivity (cal/cm s °C)	6×10^{-3}	5×10^{-3}	5.6×10^{-3}	16×10^{-3}
Specific heat (cal/g °C)	0.11	0.208	0.205	0.206
Coefficient of thermal expansion (cm/cm/°C)	10	8	10	25
Oil absorption	6	25	10	25
Dielectric constant	6.1	7.5	6.1	5.5
Refractive index	1.65	1.59	1.6	1.54–1.69
Brightness (Hunter L, 325 mesh powder)	84–96	78–95	78–98	38–45

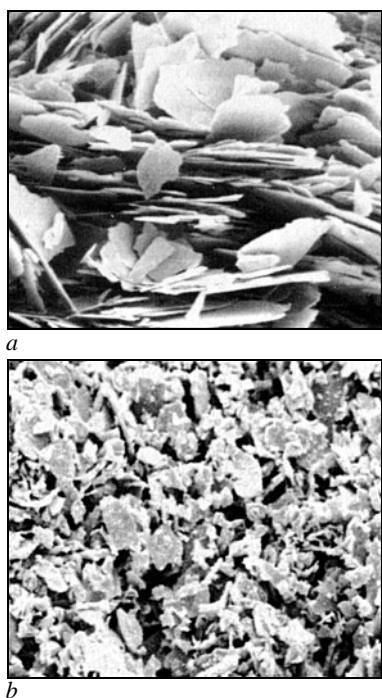


Figure 4.5 Micrograph of mica flakes. a) High aspect ratio plate-like flakes b) Superfine flakes. The plate-like form of mica flakes provides reinforcement in two directions. [866]

of 100 to 325 for muscovite mica and 20 to 200 for phlogopite mica. Mica flakes are flexible, elastic, and tough. Mica is softer (Mohs hardness of 2.5–3.0) than glass fibers or wollastonite, which minimizes abrasion, and the surface appearance of mica-filled polymers is better than glass-filled resins due to the tendency of mica to orient parallel to the mold surface during processing. The specific gravity of a high aspect ratio, surface-treated mica is 2.8. [827, 866, 860, 942]

Mica reinforcement provides enhanced flexural moduli, heat deflection temperatures, tensile strengths, dimensional stability, and sound deadening properties. Enhancement of mechanical properties varies with particle size; flexural modulus and tensile strength increase with increased particle size, while impact strength decreases. Elongation, thermal expansion, and shrinkage are reduced with mica reinforcement, and the planar orientation of the flakes reduces the nonuniform thermal shrinkage that causes warpage. Mechanical properties can be improved by surface treatment with coupling agents. Mica is acid resistant, except for concentrated sulfuric-phosphoric acid mixtures and hydrofluoric acid. Its use in polypropylene imparts a tan or brown color to the resin; it is generally used when color is unimportant or for a speckled appearance. [827, 697, 866, 942]

Commercial grades of mica are wet or dry ground. Wet ground flakes are smoother and more polished than dry ground micas, which have more jagged edges. Wet ground micas have better physical properties and higher bulk densities. [942]

Mica can be used in injection molding, extrusion, thermoforming, and rotomolding. It can be incorporated by melt compounding or sometimes by dry blending. It disperses more easily in molten resin than talc or calcium carbonate fillers or glass fibers. Mica is used as a lower cost alternative to glass fiber reinforcement of polypropylene in the automobile industry, for under the hood components (air conditioning and heater valve housings), trim, dashboard components, and grille-opening panels. [827, 866, 860]

4.6 Wollastonite

Wollastonite is a naturally occurring calcium metasilicate, composed of calcium oxide and silicon dioxide. It is a white mineral that occurs in a needle-like form; aspect ratios range from 3 to 20. It has a high melting point, high pH (9.9), and a specific gravity of 2.9, and it exhibits low moisture absorption. It is a reinforcing filler that competes with talc and mica. It provides some reinforcement in polypropylene at 40 parts per hundred (phr); reinforcement properties increase when 30 phr wollastonite is combined with 10 phr glass fiber, resulting in increases in tensile strength, flexural strength, impact strength, and heat deflection temperature. Wollastonite alone as a reinforcing filler can decrease impact strength, and its abrasivity can cause wear on processing equipment. [827, 866]

4.7 Organic fillers

Wood flour is an organic filler used in polypropylene that is formed from grinding hardwoods, sometimes blended with nutshells. It is readily available, inexpensive, and lightweight, with a specific gravity of about 1.50. It is composed of fine particles with a low aspect ratio (2.5), with particle sizes ranging from 70–500 μm . Wood flour increases resin stiffness but exhibits low temperature stability and can decompose at 190–200°C (380–400°F); in addition, its polar surface can result in poor bonding to the resin surface. Flax has also been used in polypropylene; panels in the latest VW Passat Variant station wagon are reinforced with 50% flax. [827, 866, 864]

4.8 Glass spheres

Glass spheres are sometimes used in polypropylene. Glass spheres can be solid or hollow; hollow spheres, with a density of about one-fifth that of pure resin, are used to reduce the weight of the filled plastic, while solid spheres provide strength. Commercially available sizes range from 5–5000 μm in diameter; a 30 μm diameter (325 mesh) size is commonly used in plastics. Glass spheres in polypropylene provide increased stiffness at elevated temperatures, higher compressive strength, and dimensional stability. Due to their spherical shape, they act as ball bearings in a resin, and flow properties and stress distributions are better than with high-aspect fillers. [860, 827]

4.9 Glass fibers

Glass fibers are the most widely used reinforcement in thermoplastics. They are cost-effective, and a broad range of physical properties can be achieved for a large number of applications. Glass fiber reinforcements are strands of filaments drawn to various diameters between 3.8 and 18 μm , with letter designations of B to P. The number of filaments per strand, the configuration of the strand, and the fiber length-to-weight ratio can be varied, depending on the desired properties. [827, 662]

Most plastics are reinforced with E (electrical) glass, a borosilicate glass with poor acid resistance, fair alkali resistance, good moisture resistance, and excellent electrical insulation properties. Other types of glass can provide better alkali or acid resistance (C or chemical glass), good dielectric properties (D glass), or high strength for advanced composites (S glass). Glass fibers are usually coupled or coated with sizing in order to facilitate processing, minimize fiber breakage during processing, and provide compatibility with the polymer. Sizing agents are generally proprietary organic formulations designed for the particular resin. They consist of polymers (polyvinyl acetate, polyester, epoxy, starch) that form films to hold the fibers together, amine lubricants to impart lubricity, and silane, chrome, or titanate coupling agents for polymer-fiber crosslinking. [827, 662]

Continuous and chopped strands are commonly used in polypropylene. Continuous strands are untwisted and wound onto a spool; chopped strands consist of continuous strands cut into lengths ranging from 1/8 in. (0.32 cm) to greater than 1 in. (2.5 cm) in 1/4 in. (0.64 cm) intervals. Chopped and

continuous strands are used in injection molding, at loadings of 5–30%. Mats can be made from chopped or continuous strands. Polypropylene is the most common polymer used in glass mat reinforced thermoplastics (GMT). GMT polypropylene exhibits enhanced dynamic toughness, higher energy absorption upon impact, and an excellent stiffness to

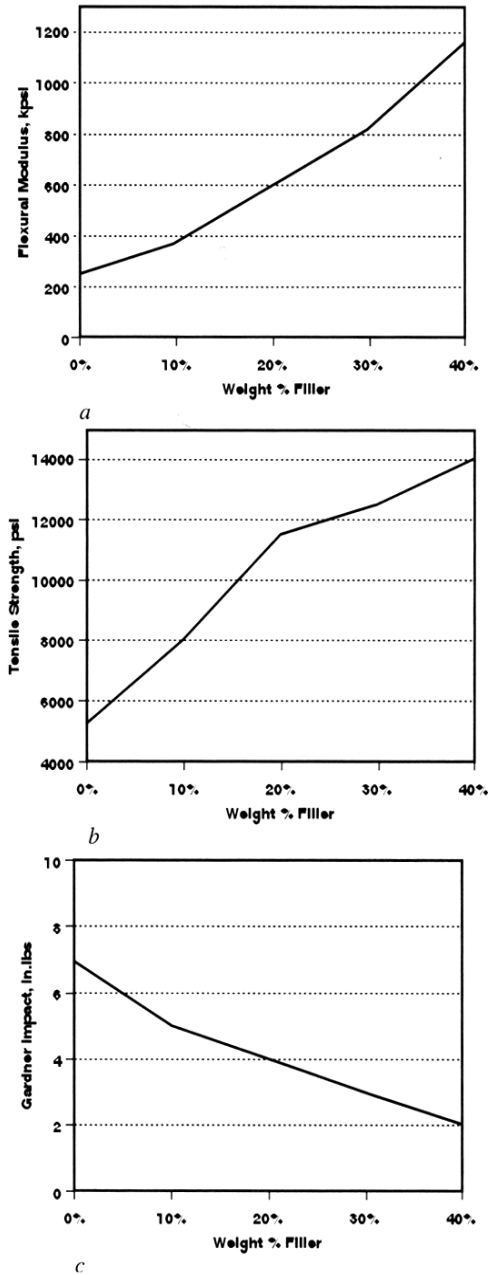


Figure 4.6 The effect of glass fiber reinforcement on mechanical properties of polypropylene. a) flexural modulus b) tensile strength c) Gardner impact strength. Flexural modulus and tensile strength increase with increasing glass fiber content; Gardner impact strength decreases. Polypropylene homopolymer (melt flow rate 12, density 0.905 g/cc) was compounded with 3/16 inch (0.48 cm) glass fibers using a twin screw extruder. [853]

toughness ratio compared to short fiber reinforced polypropylene. As a result, GMT polypropylene can compete with other polymeric composites, aluminum, and steel. [865, 827, 868]

Glass fiber reinforced resins have high tensile strength, high stiffness and flexural modulus, and high heat deflection temperatures. With 40% glass fiber reinforcement, the heat deflection temperature of polypropylene at 1.82 MPa (264 psi) increases to 150°C (300°), compared to 60°C (140°F) for the unreinforced material. Impact strength decreases in glass-reinforced resins. The effects of increasing glass fiber content on flexural modulus, tensile strength, and Gardner impact strength are shown in Figure 4.6. The abrasiveness of glass fibers can damage machinery and tooling; hardened coatings on barrels, screws and tooling can minimize abrasion. [326, 853, 865, 697, 827]

Because glass fibers orient in the flow direction during injection molding, shrinkage is greatly reduced in the direction of flow; in the transverse direction, the shrinkage reduction is not as great. Distortion problems can result from the large difference in shrinkage values, and fiber reorientation can occur where two flow fronts meet, changing the direction of shrinkage. The orientation of glass fibers makes accurate predictions of shrinkage difficult and can cause warpage; wider manufacturing tolerances are required for glass fibers than for talc or glass sphere reinforcements. [326, 853, mp 88, 697, 827]

4.10 Carbon fibers

Carbon fibers are fine filaments composed of elemental carbon. Structure can vary from amorphous carbon to crystalline graphite, providing a wide range of physical properties. Density ranges from 1.6–1.9 g/cm³. Product types range from fiber mats, with low strength and moduli, to chopped fibers and continuous filaments. Carbon fibers can provide high modulus (up to 52,000 MPa; 75 million psi), high strength (up to 3000 MPa; 400,000 psi), excellent chemical resistance, increased thermal conductivity, and a low coefficient of thermal expansion. Coupled carbon fiber-reinforced thermoplastics at 10–40% loadings have improved flexural modulus, flexural strength, and retention of me-

chanical properties in humid environments and greater creep and wear resistance compared to glass fibers. They are used in automotive, aerospace, and sporting-goods applications. They are more expensive than glass fibers; as a result, their use in polypropylene is generally restricted to applications that require electromagnetic interference and radio frequency interference (EMI/RFI) shielding capabilities. [697, 827, 879]

4.11 Applications of filled polypropylene

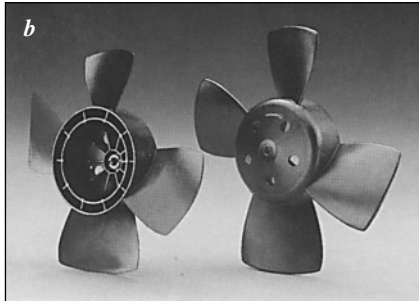
Reinforced and filled polypropylene is used in the automotive, appliance, furniture, and electrical industries. Automotive applications include glass-fiber reinforced fan mountings and shrouds, belt covers, air filters, spoilers, cooling system tanks, and talc-reinforced fans, dashboards, electric system housings, heater housings, and headlamp housings. Mineral reinforced (20%) polypropylene used in interior trim in the VW Golf provides sound deafening properties and does not cause unpleasant rattling or squeaking noises. [326, 706]

Talc-reinforced polypropylene is used in the appliance industry for washing machine powder dispensers, end plates for dryers, spray rotors for dishwashers, wastewater pump housing components, basket supports, air circulation ducts, extractor hood housings, washing machine tops, compressor supports for refrigerators and freezers, toaster and electric iron housings, and housings for coffeemakers and washing machine electronic components. Refrigerator liners made of mineral-filled polypropylene are a replacement for acrylonitrile-butadiene-styrene (ABS). [326, 697]

Other applications include lawn and garden furniture, with ultraviolet stabilizers to protect against sunlight, and lawn mower housings. Mineral-filled thermoformed packaging materials for applications such as microwaveable packaging provide high heat resistance, mechanical rigidity, durability, and low taste and odor. Examples of applications of reinforced polypropylene are shown in Figure 4.7. [851, 182, 697]

Figure 4.7 Examples of applications of reinforced polypropylene.

- a) cooling system expansion tank made from glass fiber-reinforced polypropylene
- b) fans made from talc-reinforced polypropylene
- c) clothes lifter made from talc-reinforced polypropylene
- d) toaster housing made from talc-reinforced polypropylene. [326]



Polypropylene film is one of the most versatile packaging materials. It is economical due to its low density and is replacing other materials, such as polyethylene, polyvinyl chloride, polyester, and cellophane, in packaging applications. Almost 90% of plastic packaging is used in food applications; other applications include film packaging for stationery products, cigarettes, and textiles. [794, 754, 891]

Both random copolymers and homopolymers are used in film production. Films can be unoriented, uniaxially oriented, or biaxially oriented and are defined as sheet materials that are less than 0.254 mm (10 mils) in thickness; thicker films are referred to as sheets. Resins with melt flow indexes of ~2–8 g/10 minutes are generally used in films, although higher melt flow rate resins are also used. Higher melt flow resins are used in cast film processes. [642, 788]

5.1 Unoriented film

Unoriented polypropylene films can be produced by casting or blown film processes. Chill roll casting and tubular water quenching are commonly used. Conventional air quenching, widely used for polyethylene, produces brittle films with poor clarity in polypropylene; however, newer polypropylene resins and copolymers developed for air quenched processes can provide economical alternatives to polyethylene. The tubular water quench process is commonly used to produce monolayer film. [691, 881, 890, 893, 795, 642, 894]

Unoriented films have a very soft hand and are easily heat sealed. They exhibit good heat stability, low flexural moduli, excellent puncture resistance, excellent impact strength, and low moisture permeability but provide only poor barriers to gases, such as oxygen and carbon dioxide, some perfumes, and oil such as peppermint oil. Clarity of unoriented random copolymer film is moderate and is affected by processing conditions. Because its physical properties are balanced, unoriented film is easier to process on bag making equipment than cast oriented film, and slitting and sealing is easier in the transverse direction. Applications include packaging for shirts, hosiery, bread, and produce, use as a strength and barrier layer in disposable diapers, and use in electrical capacitors. [691, 881, 890, 893, 795, 642, 894]

5.2 Cast film

Cast processes are usually used to produce uniaxially oriented film, oriented in the machine direction. Physical properties of the film depend on the degree of orientation, and a film is produced with different surface properties on each side. Oriented cast polypropylene film is clear and glossy, with high tensile strength. It is about three times stiffer and stronger than low density polyethylene film. Cast film provides good moisture barrier properties and scuff resistance at low cost. Low temperature brittleness is a problem with homopolymer polypropylene film; this can be overcome by the use of a copolymer resin. [794, 642]

A water bath is sometimes used instead of a chill or casting roll; the water bath process quenches the melt on both sides at the same time, producing a film with the same surface properties on each side. The machine direction orientation in the water bath process is somewhat different than that obtained using the casting roll, and the very rapid quenching lowers the crystallinity, producing a tougher film. [642]

Tear initiation, by impact, puncture, or ripping, is difficult in oriented polypropylene films (OPP); once initiated, however, the resistance to tear propagation is low. Tear strength depends on grade and process conditions and on whether the tear propagates in the machine or transverse direction. A tear strip is usually incorporated in OPP film packs to facilitate opening. [642, 893]

5.3 Biaxially oriented film

Biaxially oriented polypropylene film (BOPP) is film stretched in both the machine and transverse directions, producing molecular chain orientation in two directions. BOPP film is produced by the tubular process, in which a tubular bubble is inflated, or a tenter frame process, in which a thick extruded sheet is heated to the softening point (not to the melting point) and is mechanically stretched by 300–400%. Stretching in the tenter frame process is usually 4.5:1 in the machine direction and 8.0:1 in the transverse direction, although ratios are fully adjustable. It is a widely used process, more common than the tubular process, and a glossy, transparent film is produced. Biaxial orientation results in increased toughness, increased

stiffness, enhanced clarity, improved oil and grease resistance, and enhanced barrier properties to water vapor and oxygen. Impact resistance, low temperature impact resistance, and flexcrack resistance are substantially modified. BOPP films are used in food packaging and are replacing cellophane in applications such as snack and tobacco packaging due to favorable properties and low cost. [642, 891]

Oriented films can be used as heat shrinkable films in shrink wrap applications or can be heat set to provide dimensional stability. Heat sealing is difficult in BOPP films but can be made easier by either coating the film after processing with a heat-sealable material (such as polyvinylidene chloride) or by coextrusion with one or more copolymers before processing, to produce layers of film. Copolymers used in sealing layers must have high gloss and clarity and should have low sealing temperatures to prevent distortion of the oriented

polymer during sealing. Random copolymers containing 3–7% ethylene are often used as sealing layers; the lower melting point (<132°C; <270°F) results in a 30% increase in line speeds, and they can be recycled with no significant loss of strength or clarity. Coating or coextrusion increases the barrier properties of BOPP film, decreasing its permeability to gases. Common barrier polymers are ethylene vinyl alcohol, polyvinylidene chloride, and polyamide; five or more layers may be coextruded or laminated, or the barrier polymer can be dispersed in the matrix polymer. [890, 891, 642]

Some typical properties of cast, uniaxially oriented and biaxially oriented polypropylene film are listed in Table 5.1. Properties of films made using Novolen (BASF) homopolymers, random copolymers, and block copolymers are listed in Table 5.2. [642, 691, 756]

Table 5.1 Properties of Oriented Polypropylene Films

Property	ASTM Test Method	Cast, Uniaxial Orientation	Biaxial Orientation
Area Factor in 2/lb./1 mil film	—	30,400–31,300	30,600
Specific Gravity, g/cc	D1505	0.885–0.905	0.902–0.907
Tensile Strength, psi	D882	4500–7000	7500–40,000
Elongation, %	D882	550–1000	35–475
Tear Strength, g/mil Propagation	D1922	25 MD* 600 TD*	3–10
Fold Endurance	D2176	Very High	Excellent
24 hr. % Water Absorption	D570	0.005	0.005
Water Vapor Transmission Rate, g/mil/100 sq. in./24 hr. @ 100°F	E96	0.7	0.25
Oxygen Permeability, cc/100 sq. in./mil/24 hr./atm. @ 77°F	D1434	150–240	160
Heat Sealing Temperature Range, °F	—	285–400	—
Gloss, %	—	90	95
Haze, %	—	1–2	1–2

*MD = Machine Direction *TD = Transverse Direction

Table 5.2 Properties of Novolen cast film (50 µm gauge)¹

Property		Unit	Test Method	Block copolymer	Random copolymer		Homopolymer		
Grade				2309KX	3200 MCX	3520 LX	1125N	1127MX	1325L
Additives				None	None	antiblock agents	slip, antiblock agents	slip, antiblock agents	slip, antiblock agents
Melt flow rate		g/10 min	ISO 1133	4	8	5	11	8	5
Gloss	20°	%	DIN 67530	5	130	130	110	95	115
Haze		%	ASTM 1003	28	0.5	0.3	2.3	3.0	1.7
Tensile strength at break	machine direction	MPa	DIN 53455	55	37	32	42	44	35
	transverse direction	MPa	DIN 53455	36	35	30	38	40	33
Elongation at break	machine direction	%	DIN 53455	750	730	750	680	700	750
	transverse direction	%	DIN 53455	720	750	760	720	730	780
Dart drop impact resistance F50		g	ASTM 1709	500	450	>800	280	300	800
Modulus of elasticity in flexure	machine direction	MPa	DIN 53121	650	480	300	700	680	370
	transverse direction	MPa	DIN 53121	640	470	310	670	650	350
Coefficient of friction			DIN 53375	0.90	Not measurable	Not measurable	0.25	0.17	0.13

¹ Data was obtained using film specimens prepared by internal standards. Film properties depend considerably on processing conditions. This must be taken into account when comparing these data with data obtained under different processing conditions.

Polypropylene sheets (greater than 0.254 mm (10 mils) in thickness) are used in applications such as plating and etching equipment, clean room equipment (shells for wafer machines, modular hood systems), ventilation equipment, cookie trays, medical devices, liners for hatcheries and irrigation canals, and geomembranes. [691, 755, 894, 795, 773]

Polypropylene is more difficult to thermoform than other olefins due to its sharp melting point and low melt strength; resins with low melt flow rates are necessary for adequate melt strength. New homopolymer and copolymer grades with high melt strength have been developed that provide a cost-

effective alternative to polyvinyl chloride and polyethylene, and special grades are available for food contact applications or for applications that require flame retardancy. [691, 755, 894, 795, 773]

Polypropylene sheets can provide excellent impact resistance, puncture resistance, and chemical resistance to a range of acids, alkalis, and solvents. They exhibit good heat sealing behavior and blush resistance and are free from plasticizers and heavy metal-based stabilizers. Several properties and applications of Versadur polypropylene sheet (HPG International, Inc.) are shown in Table 6.1. [894, 755]

Table 6.1 Properties of Versadur Polypropylene Sheet*

Property	ASTM Test Method	500 Series: Extruded Homopolymer, Stress relieved	550 Series: Extruded Homopolymer, Flame Retardant, Stress-Relieved
Density (g/cm ³)	D 792	0.91	0.98–1.02 at 23°C
Water Absorption (%)	D570	0.02	<0.01
Tensile Strength at Yield (psi)	D 638	4900	3770
Modulus of Elasticity (psi)	D 638	210,000	297,000
Ultimate Elongation (%)	D 638	200	30
Izod Notch Impact Strength (@ 73°F; ft. lbs/in. ²)	D 256	1.9	1.8
Rockwell Hardness (R)	D 785	92	101
Durometer (Shore A/Shore D)	D 2240	98.1/85.2	—
Heat Distortion Temperature (°F) at 66 psi at 264 psi	D 648	210 135	266 149
Vicat Softening of Expansion (°F)	D 1525	300	306
Linear Coefficient of Expansion (in./in. °C)	D 696	9×10^{-5}	8.25×10^{-5}
Volume Resistivity (ohm-cm)	D 257	$>10^{16}$	$>6.2 \times 10^{16}$
Flammability (1/8" +)	UL	—	UL94 V-0
Standards and Specifications: 500 Series Extruded Homopolymer Sheet, Stress-Relieved			
ASTM D-4101, Group I, Class I, Grade II			
FDA Regulation Title 21 CFR 177.1520 (C1.1)			
Federal Specification LP-394B, Type I (GP), Type III, Grade IIIA, Class III			
USDA Approval for direct contact with meat and poultry products (natural and white colors)			
Military Standard D / N / A			
UV Radiation Exposure — 500 hours, no visible change			
California Proposition 65 — Safe Drinking Water and Toxic Enforcement Act — Passes			
Applications	500 Series, Extruded Homopolymer	550 Series, Extruded Homopolymer, Flame Retardant	
	Semiconductor processing equipment Laboratory equipment Food grade applications Prosthetics Etching and plating lines Protective equipment Acid tanks	Semiconductor processing equipment Etching and plating tanks Protective equipment	

*Versadur polypropylene sheet from HPG International, Inc.

Polypropylene is widely used in the production of fibers, for use in carpeting, rope and twine, textiles, automobile interiors, geotextiles, nonwoven products such as diapers, and other applications. Polypropylene is one of the major synthetic fibers used for carpeting, in addition to nylon and poly(ethylene terephthalate), with a market share of 25%. Fibers are one of the most important applications for polypropylene homopolymer. Due to the melt flow properties of polypropylene, fiber formation is easier than in other polymers, and its relatively low density results in a higher yield of fiber per pound of material. Properties of polypropylene useful for fiber applications are given in Table 7.1. [708, 691, 795, 719]

Table 7.1 Useful Properties of Polypropylene in Fiber Applications

Property	Application
Low thermal conductivity	Insulating material
Rot resistance	Civil engineering fabric
Hydrophobicity	Diaper or sanitary napkin cover stock
Chemical resistance	Blood filters
Stain resistance	Upholstery
Resistance to insects	Agricultural bags
Low static build-up	Carpet face fiber

Polypropylene fibers are produced by melt spinning, a process in which molten polymer is forced through a spinnerette, a metal plate that contains as many as 50–100 holes or capillaries, each with a diameter of <0.2 mm (0.008 in.). The molten polymer emerges as continuous strands of fiber that are cooled or quenched using water or a current of air. The fibers are then drawn by heating to a temperature close to the melting point and stretching; this reduces the fiber cross-section and produces orientation in the fibers, resulting in an increase in tensile strength. Physical properties of the oriented fiber are highly dependent on the amount and conditions of drawing. Melt spinning produces different types of fibers, with differing properties and applications, depending on the processing equipment and conditions. [642, 662]

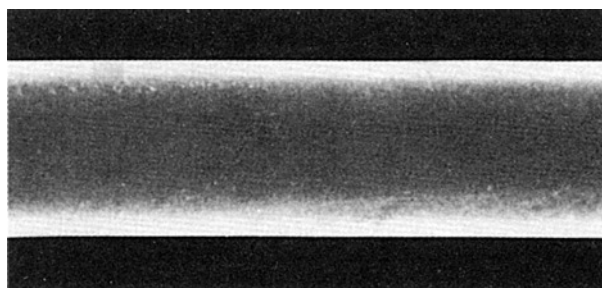


Figure 7.1 A monofilament fiber or yarn. A single filament is extruded by melt spinning, then drawn to produce orientation. Sizes of monofilaments range from 75–5000 denier. [869]

7.1 Monofilaments

Monofilaments are ribbons of polypropylene composed of a single extruded filament (Figure 7.1) produced by melt spinning; virtually all monofilaments are water quenched. Sizes of monofilaments range from 75–5000 denier (1 denier = weight in grams of 9000 m of fiber). Polypropylene resins with high molecular weights or low melt flows (~1–4 g/10 min) and a medium to wide molecular weight distribution are used in monofilament production. [705, 788, 642]

Monofilaments are used in weaving stiffer products such as rope or twine; ropes have high wear resistance and tensile strength, do not absorb water, float due to the low density of polypropylene, and retain strength when wet. Monofilament fibers have a highly reflective and translucent surface, limited absorption capacity, high stiffness, good tensile strength, and excellent surface particle release that makes them easy to clean. Excellent diameter control during processing produces fabric with precise and measurable openings. [705, 788, 869]

7.2 Multifilaments

In multifilament yarns, several individual filaments, commonly ≤ 75 denier, are gathered into a single continuous bundle (Figure 7.2). Filaments of ≤ 30 denier are air quenched; the slow cooling rate produces a very highly ordered crystal structure, and fibers exhibit high thermal stability and low creep. Larger filaments cool more slowly, and air quenching is not economical; water quenching is used instead. The rapid cooling in water quenching allows very little time for the development of crystalline structures; as a result, drawn,

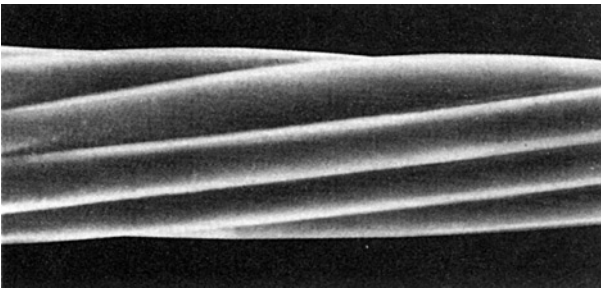


Figure 7.2 A multifilament fiber or yarn. Individual filaments, each ≤ 75 denier, are produced by melt spinning, drawn, and gathered into a single continuous bundle. [869]

water-quenched fibers are tough, with high tenacity and moduli. [642]

Diameter control of multifilaments is more difficult than in monofilaments; filaments generally must be twisted to hold them together during weaving. Particles are captured between filaments, making multifilaments difficult to clean. They are flexible and pliable with excellent fatigue resistance and have excellent tensile and knot strength. They have a dull, non-reflective surface and a good absorption capacity. Useful properties of multifilaments are listed in Table 7.2. [869, 705]

7.2.1 Continuous filament and bulked continuous filament yarns

Continuous filament yarn (CF) and bulked continuous filament yarn (BCF) are used in the production of floorcoverings, fabrics, belts, and ropes. Medium-to-high molecular weight polypropylene resins are generally used. CF yarn is multifilament yarn wound onto tubes or cones; BCF yarn is treated (texturized or crimped) to give it three-dimensional bulk (Figure 7.3). The texturing process consists of heating the yarn to slightly below its melting point, deforming it by turbulent air flow, a hot knife edge, or steamjet, and allowing it to cool in the deformed state. When slightly stretched and allowed to relax, the yarn “blooms” and develops a bulked appearance. It is then

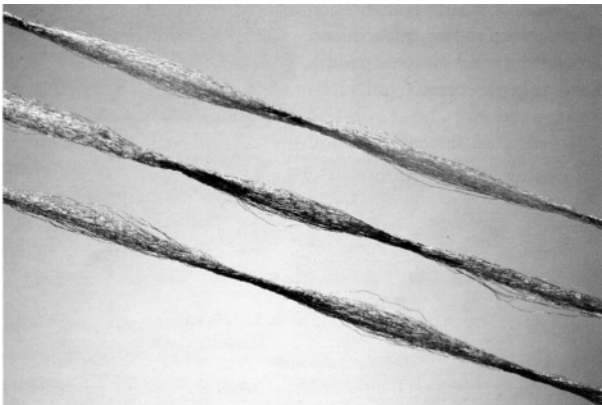


Figure 7.3 Bulked continuous filament yarn. Continuous filament yarn is texturized or crimped to increase three-dimensional bulk. The texturing process consists of heating the yarn to slightly below its melting point, deforming it, and allowing it to cool in the deformed state. When stretched and allowed to relax, the yarn develops a bulked appearance useful in carpeting. [705]

wound onto tubes. Typical denier range of BCF yarns is 3 to 30. [705, 642]

Sportswear and leisure wear fabrics, such as activewear, swimwear, intimate apparel, jeans, and hosiery, are generally made from low-titer CF or BCF yarn; yarns are frequently combined with other textiles during processing. Due to the low thermal conductivity of polyolefins — the lowest of traditional apparel fibers — polypropylene in layered clothing traps air in the space between layers, providing warmth in cold weather. When exposed to air, polypropylene clothing “breathes” due to the permeability of polypropylene to gases such as oxygen, providing cooling in warm weather. [719, 691]

The wicking action of polypropylene makes it useful in activewear; perspiration is not absorbed but is passed through the fabric to the other side through capillary action, where it can be absorbed by a layer of absorbent material such as cotton. A dry environment is then maintained. [705, 719]

The chemical resistance of polypropylene makes it resistant to stains and odors, and, along with low moisture absorption, provides resistance to mold, mildew, and bacteria. Because polypropylene is colored by pigments and not dyes, fabrics are resistant to fading, and light and dark colors can be combined for washing. Polypropylene fabrics can be dried in home dryers at low temperatures. [719, 897]

Polypropylene floorcoverings are usually made of coarse BCF yarn; resins with low to medium viscosity are used in fiber spinning. Although nylon is the primary polymer used in carpets (~65% market

Table 7.2 Properties and Applications of Multifilaments

Properties	Applications
Good skin tolerance Excellent color fastness Light weight Good insulation capacity Soft textile handle Low electrostatic discharge Hydrophobic	Floorcoverings Sports and leisure wear Belts Ropes and cords Furniture upholstery Woven screening

share), the use of polypropylene in loop pile carpets has gained in market share due to a lower resin price. Polypropylene carpets have excellent stain resistance due to the polymer's excellent chemical resistance and hydrophobicity, and stains and soils remain on the surface for easy cleaning. Polyolefins are the highest rated carpet fibers for ease of stain removal. Because polypropylene is pigmented and not dyed, the color will not bleed or run; fade resistance is three times the industry standard. Carpets are mildew-resistant, with low odor, very good abrasion resistance, and a fair to good texture. Low static build-up makes vacuuming more efficient, and polypropylene carpets can be recycled for use in automobile parts and structural products. [705, 708, 897, 707, 719, 898]

A disadvantage of polypropylene is that it cannot be effectively heat-set, and carpets exhibit poor resilience or recovery — the ability of the carpet tufts to recover from repeated bending — about half that of nylon. In a cut pile carpet, polymer fibers are twisted and heat-set. Heat-setting is not essential in loop pile carpets. In heat-setting, the yarn is twisted, then heated to a temperature above that of the glass transition temperature of the polymer. At this temperature, polymer chains are capable of greater movement, and they relax somewhat from their oriented configuration into a twisted configuration. In polymers containing polar elements (nitrogen, oxygen) such as nylon, hydrogen bonding occurs and helps to maintain the twisted configuration. If the glass transition of the polymer is above room temperature, the twisted shape is retained or “frozen in”, due to very limited chain movement below the glass transition temperature, when the fibers are cooled to room temperature. This occurs in nylon fibers, with glass transition temperatures ranging from 40–80°C (100–180°F). In polypropylene, glass transition temperatures range from –35–25°C (–31–77°F), so that the twisted shape is not “frozen in”. [897, 707]

Poor resilience can be compensated for by using more fiber, forming a dense pile that supports the tufts so that they compress like a spring instead of bending. Improved texturizing techniques and extrusion processes can also increase the resilience. [898, 707]

A new, experimental Catalloy process produces polypropylene copolymer fibers with improved resilience. The Catalloy process is a gas phase polymerization of two or more alpha olefin monomers, in which physical and thermal proper-

ties can be tailored by proper comonomer selection and selective incorporation of the comonomer into the polymer chain. Catalloy process fibers display excellent twist retention, possibly due to a broader melting range (by differential scanning calorimetry). Melting begins at a lower temperature, so that some regions melt while others are still oriented; this selective melting allows greater yarn contraction during heat-setting and greater twist retention. Catalloy process fibers also have lower tenacity and higher yield elongation than polypropylene fibers. They are easier to process, are softer and less harsh and exhibit more elastic behavior. Cyclic recovery is 2.5 times greater than polypropylene. [897]

Polypropylene fibers are used in carpets in public buildings and office buildings; residential carpeting was not initially an application for polypropylene due to limited styling capabilities and its lack of resilience in cut pile carpeting. The addition of hindered amine light stabilizers provides increased sunlight resistance and has extended its use in all-glass office buildings. Polypropylene performs best in multicolor low pile height loop pile carpets in uses where pile height loss may not be noticed, in high weight cut pile carpets, in which low resilience and heat-settability are not as important, and in loop pile berbers in low-traffic residential settings. [897, 707]

7.3 Fiber staple

Staple fibers are produced by collecting filament into a tow, a loose rope. The tow is then stretched, crimped — which produces a short, repeating zig-zag pattern in the filaments — and chopped into short lengths (0.64–5.72 cm; 0.25–2.25 in.). The discontinuous fibers are then pressed into a bale. Denier of staple fibers generally ranges from 1–10. An example of staple fibers is shown in Figure 7.4. [642, 705]

Staple fibers are used in textiles — floorcoverings, geotextiles, clothing — and sanitary non-woven materials. Fibers with very fine titers (<4 dtex) are used as coverstock for diapers and sanitary products. Due to the hydrophobic nature of polypropylene and its wicking action, body fluids are transported through the coverstock into absorbent layers below, and the layers next to the skin remain dry. Fibers with higher titers (>4 dtex) are used predominantly for floorcoverings (needlepunched carpets), artificial grass, in automo-



Figure 7.4 Staple fibers. Filaments are collected to form a tow, which is then stretched, crimped, and chopped into discrete lengths. The discontinuous fibers are then pressed into a bale. Denier of staple fibers ranges from 1–10. [705]

biles (for floor coverings, boot linings, and rear parcel shelves), and in geotextiles used in drainage, filtering, and soil stabilization. When processed into spun yarn, staple fibers are used in upholstery fabrics, bed linen, and sports and leisure apparel. Useful properties of polypropylene staple fibers include low weight, high chemical resistance, low thermal conductivity, hydrophobicity, and moisture transfer (no absorption). [705]

7.4 Slit Tape

Slit tape, also called film yarn, is produced by slitting flat or blown film. A thin, molten film is extruded and cooled in a water bath; it is then slit into many small tapes by a series of spaced blades. The slit tapes are then drawn and wound onto tubes. Tapes can be fibrillated by passing the slit tape over a rotating roll that contains rows of offset pins. The roll surface speed is faster than the tape speed, so that a series of cuts is formed in the tape, forming a fibrous network. Fibrillated slit tapes are used in applications such as typing twines and face fiber for synthetic grass carpeting. [705]

Mechanical properties of slit tapes are dependent on the molecular weight (or melt flow index) of the polymer. High molecular weight (low melt flow, such as 230/2.16 of 2 g/10 min) resins are used in woven-tape bags and carpet backings, applications that require high tensile strength, low elongation, and a low tendency to split. Resins with a higher melt flow, such as 230/2.16 of 3.5 g/10 min, are more fibrous and have a greater tendency to split; they are used in rope, baler twine, and packing string and are usually fibrillated. Other properties of

polypropylene slit tape include low density, neutral odor, no water absorption, and resistance to chemicals and rotting. Properties of slit tapes are influenced by film processing conditions; conditions such as film thickness and stretching and cooling method influence properties such as tensile strength, elongation, and shrinkage. Polypropylene slit tape has replaced natural raw materials (sisal, jute, and hemp) in applications such as carpet backing, due to superior properties. [705, 642]

7.5 Spunbonded and melt-blown

In spunbonded fibers, also called air attenuated fibers, polymer is extruded through a spinneret into continuous filaments, as in multifilament processing, but air is used to draw the filaments. Fibers are separated by air jets or electrostatic charge during the spinning process. They then pass through an air chamber, where they are drawn and oriented by rapidly moving hot air (~250°C; 480°F at 650 ft/min). At the end of the chamber, they are randomly blown onto a moving perforated belt, forming a web; the web is then bonded by heat or chemical adhesives to form a non-woven scrim. Spunbonding is a one-step process for manufacturing nonwoven fabric from plastic resin. The production of melt-blown fibers is similar to spunbonded fibers, but discontinuous filaments are used, with smaller fibers than spunbonded. [662, 788, 642]

Spunbond fabrics are relatively easy to produce and can be formed in a variety of weights and styles. Weight per unit area, determined by thickness, fiber denier, and number of fibers per unit area, ranges from 10 to 800 g/m²; typical values are 17–180 g/m². Applications generally require resins with high melt flows and very narrow molecular weight distributions. Low viscosity resins (i.e. MFR 230/2.16 of 25 g/10 min) are used for sanitary nonwoven applications, such as diapers, feminine hygiene products, or products for the incontinent, with an average filament fineness of 2 dtex and a weight per unit area of 20 g/m². For coarser geotextile applications (~10 dtex fiber fineness, weight per unit area of 130 g/m²), higher viscosity resins (MFR 230/2.16 of 18 g/10 min) are used. [705]

Melt-blown fibers are fine, with a diameter of ~3 μm, an order of magnitude smaller than the smallest diameter of spunbond fibers, and a titer of <1 dtex. The fine, mostly unoriented fibers form a

dense, uniform filament distribution, and the web is weak and easily distorted. [662, 705]

Spunbond and melt-blown fibers are frequently combined in products to provide optimum properties. In sanitary nonwoven products, which require softness, good moisture transport, and high tear strength even when wet, spunbond fibers provide tear resistance, moisture removal, and minimal rewetting due to a nonuniform filament distribution. [662, 705]

Properties of polypropylene spunbonds include high strength, low weight, hydrophobicity, good skin tolerance, chemical and rot resistance, and low thermal conductivity. In addition to material characteristics, the processing parameters and bonding methods affect fabric properties. For example, fiber webs bonded by calendering, which uses pressure to compress the fiber structure, are thinner than needle-punched webs, which pushes fibers aligned with the fabric axis (x, y plane) into

the thickness direction (z direction). Properties can be tailored to the requirements of a particular application. Geotextiles all require high tear strength but may require special properties depending on the particular function (protect, reinforce, drain, filter, separate); for example, filtering geotextiles may require a special pore structure to prevent sludge formation, while puncture resistance is necessary for a protective geotextile. [662, 705]

Other applications include suits for protection against dirt, dust, moisture, and other contamination, requiring breathability and light weight, and agricultural nonwoven materials, used for seed and plant stock protection. Polypropylene spunbonds provide excellent air, light, and water permeability while protecting the plants and seed against cold, insects, and bad weather. [705]

8.1 General characteristics of polymeric foams.

Polymer foams are composed of a cellular core structure that is created by expansion of a blowing agent (See *Blowing Agents* in Chapter 3.12). Foam structures consist of at least two phases, a polymer matrix and gaseous voids or bubbles. An open-cell or closed-cell structure is formed, with cellular walls enclosing the gaseous voids. In closed cell foams, the gas cells are completely enclosed by cell walls, while in open-cell foams, the dispersed gas cells are unconfined and are connected by open passages. The presence of voids or discontinuities due to the cellular structure reduces material consumption. A blend of polymers can be present in the matrix, in addition to polymeric or inorganic fillers, and the polymer can be stabilized against cell rupture by crosslinking. Foams can be flexible or rigid; closed-cell foams are generally rigid, while open-cell foams are more flexible. [936, 937, 904, 903, 905, 772]

Plastic foam densities range from about 1.6–960 kg/m³ (0.1–60 lb/ft³); mechanical properties are usually proportional to foam density. Low density (~30 kg/m³), flexible polymer foams are used in applications such as furniture and automotive seating; high density foams are required for structural, load-bearing applications. Mechanical properties of conventional polymer foams are lower than in solid parts due to a lower material content; however microcellular foams — foams with a pore or cell size of 1–10 μm — provide good mechanical properties in addition to weight reduction. The microstructure of a microcellular foam is shown in Figure 8.1. [936, 848, 847, 849]

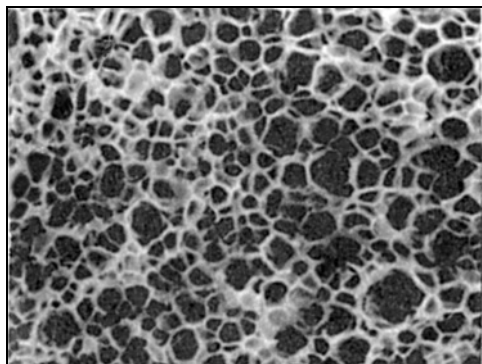


Figure 8.1 Microstructure of a typical microcellular foamed polymer. [905]

8.2 Comparison with other foamed polymers

Polyethylene, polyurethane, and polystyrene are the most common polymeric foams; however, polypropylene foams can provide favorable properties at a lower material cost. Polypropylene is stiffer than polyethylene and performs better in load bearing or structural applications. The low glass transition temperature of polypropylene compared to polystyrene provides increased flexibility and impact strength. [848, 847, 905]

8.3 Polypropylene foam processing properties

Polypropylene is difficult to foam due to a weak melt strength and low melt elasticity. Melt strength is the resistance of the melt to extension, while melt elasticity is a measure of elastic recovery. Melt strength and melt elasticity are directly related; the higher the melt elasticity, the higher the melt strength. With weak melt properties, cell walls separating gas bubbles in the foaming polymer are not strong enough to bear the extensional force as the gas expands, and they rupture. As a result, polypropylene foam has a high open cell foam content, which is unsatisfactory for many applications. Melt strength is commonly increased by polymer modification, such as crosslinking; other methods include the use of high injection pressures (>3.5 MPa), two blowing agents, or two polypropylene resins with different viscosities. [772, 903, 904]

Semicrystalline polymers are generally more difficult to foam than amorphous polymers. The morphology and degree of crystallinity of semicrystalline polymers influence the solubility and diffusivity of the blowing agent and the cellular structure of the foam. The gas resulting from use of the blowing agent does not dissolve in the crystalline regions, so that absorption and diffusion occurs mostly in the amorphous polymer regions. As a result, bubble nucleation is nonhomogeneous, and the cell structure is nonuniform. In experiments with microcellular polypropylene foams, resins with 46% crystallinity produced a nonuniform cell structure, while a crystallinity of 41% resulted in a uniform cell structure. [906, 905, 901]

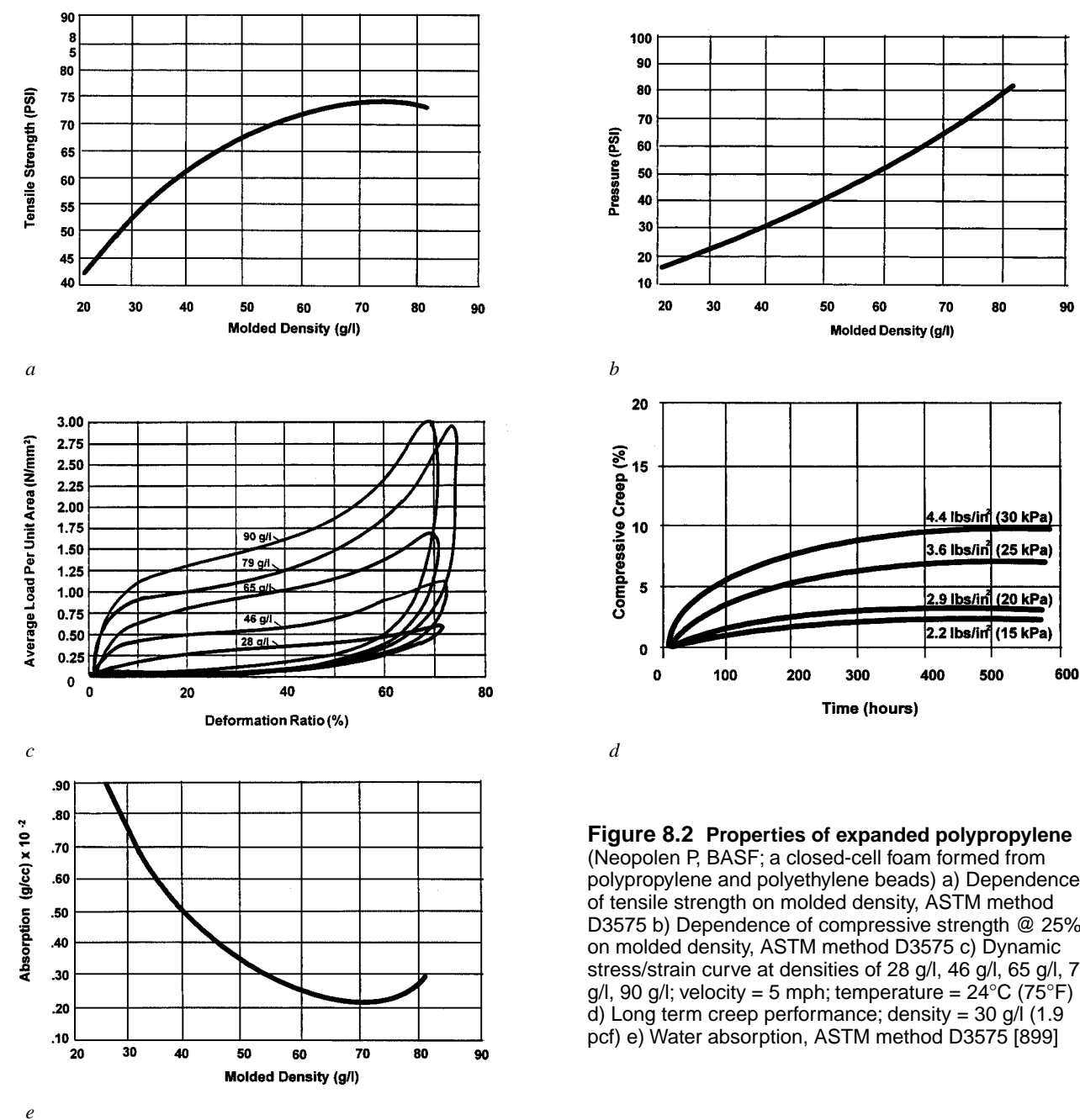


Figure 8.2 Properties of expanded polypropylene (Neopolen P, BASF; a closed-cell foam formed from polypropylene and polyethylene beads) a) Dependence of tensile strength on molded density, ASTM method D3575 b) Dependence of compressive strength @ 25% on molded density, ASTM method D3575 c) Dynamic stress/strain curve at densities of 28 g/l, 46 g/l, 65 g/l, 79 g/l, 90 g/l; velocity = 5 mph; temperature = 24°C (75°F) d) Long term creep performance; density = 30 g/l (1.9 pcf) e) Water absorption, ASTM method D3575 [899]

8.4 Properties of polypropylene foams

Properties of polypropylene foams include good heat resistance, high chemical resistance, and good insulation. Polypropylene’s high melting point makes it useful in heat-sensitive applications such as hot metal or glass processing; some foams can withstand temperatures as high as 120°C (250°F) without warpage. Polypropylene does not absorb water but is permeable to water vapor and other gases, and it is mold- and mildew-resistant. Several properties of commercial polypropylene or polypropylene blend foams are given in Tables 8.1 and 8.2 and Figure 8.2. [843, 937, 907]

Table 8.1 Properties of Microfoam Extruded Foam Sheet¹

Property	Unit	Microfoam
Density	kg/m ³	10
Cell Size	mm	0.5–1.0
Tensile Strength	kPa	240 ²
Tensile Elongation	%	190 ²
Thermal Conductivity	W/(mK)	0.042
R-Factor		3.7 ³

¹ Microfoam from Astro-Valcour, Inc.
² Average of two directions
³ Rated at 1 in. thickness

Table 8.2 Permeability of Microfoam¹ to Gases and Moisture

	Permeability
Water Vapor (g/100 in ² /24 hr)	7.3 ²
Oxygen (cc/100 in ² /24 hr)	1475
Carbon Dioxide (cc/100 in ² /24 hr)	5000
Water Absorption (lbs/ft ²)	0.04

¹ Microfoam is a closed-cell, low density polypropylene foam from Astro-Valcour, Inc.

² Higher numbers indicate that vapors are transmitted more readily

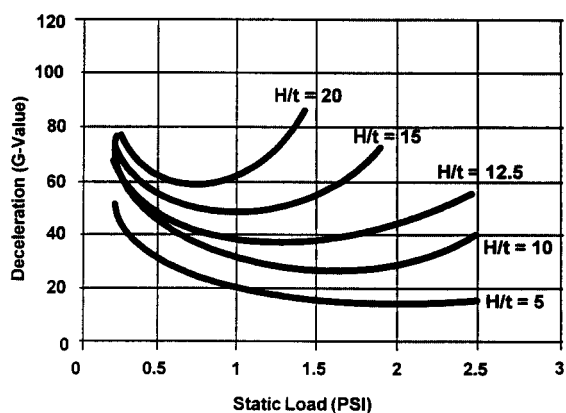
8.5 Applications of polypropylene foams

Polypropylene foams are used in packaging, automotive, insulation, and structural applications. They are used in concrete insulating blankets and as overwinter protection for plants, flotation booms for oil and chemical spills, and protection for buried pipelines. Polypropylene foams are used to provide cushioning and surface protection in the packaging of electronics, furniture, appliances, and

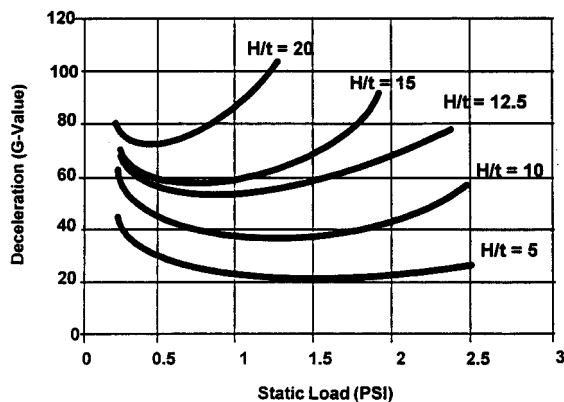
agricultural and construction products. Low density foams (>90% voids) are generally used for sound or heat insulation; medium density foams (50–90% voids) are commonly used in packaging. High density foams (<50% voids) are used in structural applications. [901, 907, 899]

Properties useful in packaging and automotive applications include shape retention and the ability to withstand repeated impacts without breakage or a decrease in properties. Impact cushioning is especially important in the packaging of heavier products, such as appliances, electronic components, and computers. The dynamic cushioning performance of expanded polypropylene (BASF) is shown in Figure 8.3. [901, 907, 899]

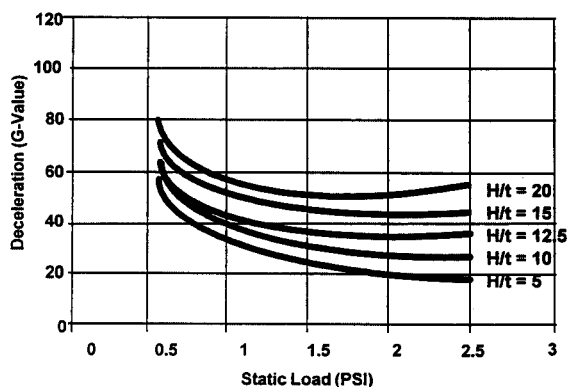
The interior chassis of a Hewlett Packard workstation (HP 700) used expanded polypropylene (EPP) foam to provide cushioning and structural support. EPP replaced conventional metal and plastic chassis structures that required assembly, resulting in a 50% reduction in assembly time and a 30% reduction in weight, and the foam protected the



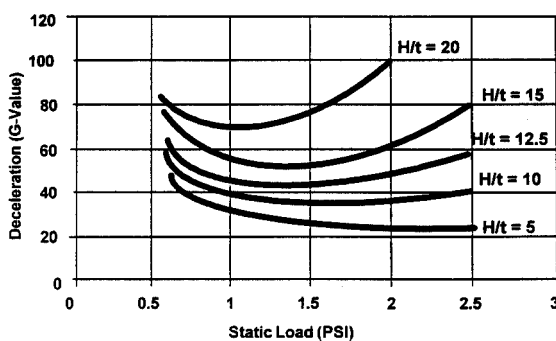
a



b



c



d

Figure 8.3 The dynamic cushioning performance of expanded polypropylene (Neopolen P; BASF). H/t = drop height/cushion thickness ratio a) initial impact, foam density = 20g/l (1.3 pcf) b) 2 to 5 impacts, foam density = 20g/l (1.3 pcf) c) initial impact, foam density = 30 g/l (1.9 pcf) d) 2 to 5 impacts, foam density = 30 g/l (1.9 pcf) [899]

computer components from impact damage during shipping. [899]

Polypropylene foams find greater use in automotive applications than LDPE due to the ability to withstand higher service temperatures; LDPE foams can only be used at service temperatures of up to 80°C (176°F). The use of polypropylene foams in automotive applications is expected to increase with the development of new applications, such as the use of molded foam beads (expanded polypropylene) as energy absorbers in bumpers. [937, 899]

Automobile applications include head and side impact energy absorbers, instrument panels, tool caddies, door liners, sun visors, sound barriers, firewalls, and heat shields. Bumper cores, door panels, and glove compartments can be made from dual density foams, in which low and high density foams are molded together in one operation, replacing monodensity foams that require thermoplastic inserts at high stress areas. European glove boxes use a talc-reinforced polypropylene carrier, EPP foam, and a thermoplastic olefin skin to provide impact protection. Dual density foams simplify processing and reduce weight by replacing metal backing, polyurethane foam, and vinyl skins. [899, 937]

Automotive interior trim and other parts such as bicycle helmets (Figure 8.4) can be produced with a solid, integral skin on one surface that does not need a separate covering. The bicycle helmet has a leather-grain texture on the outer skin surface, while the usual bead-foam appearance shows on the inside and around the edges of the helmet. [899]



Figure 8.4 A bicycle helmet with an integral skin, molded from expanded polypropylene (BASF). The usual bead-foam appearance shows on the inside of the helmet and around the sides, with a leather-grain texture on the outer skin surface. To form an integral skin, the bead-molding process is modified by a high pressure (10–12 bar) steam chamber on the side of the mold where the skin is desired. High pressure steam does not penetrate the mold cavity but only heats the tool enough to melt the beads and form a skin. [899]

Other applications of foamed polypropylene include hairbrush backs, shoe heels, toothbrush backs, and steering wheels. Hairbrush backs molded from 60% general purpose polypropylene (GPP) and 40% foamed polypropylene (Tenite P2635–08AA; Eastman Plastics) required a cycle time of 67 seconds, compared to 97 seconds for ABS. Shoe heels, molded with a blend of 90% GPP and 10% foamed polypropylene, were molded ten seconds faster than with ABS. Blends of GPP and foamed polypropylene produce small, uniform cells that increase in number as the concentration of foamable polypropylene increases, and large voids and sink marks in the part are eliminated with the optimum blend (10%, 20%, 30%, and 40% of foamed polypropylene for shoe heels, toothbrush backs, steering wheels, and hairbrush backs, respectively). An unreinforced steering wheel molded with a 60% GPP–40% foamable polypropylene blend is shown in Figure 8.5. [727]

Typical mechanical properties of two different parts (Moldings A and B) made with 100% foamable polypropylene (Tenite P2635–08AA) are shown in Table 8.3. Mold shrinkage values for typical parts made with general purpose polypropylene, foamable polypropylene, and blends are given in Table 8.4. [727]

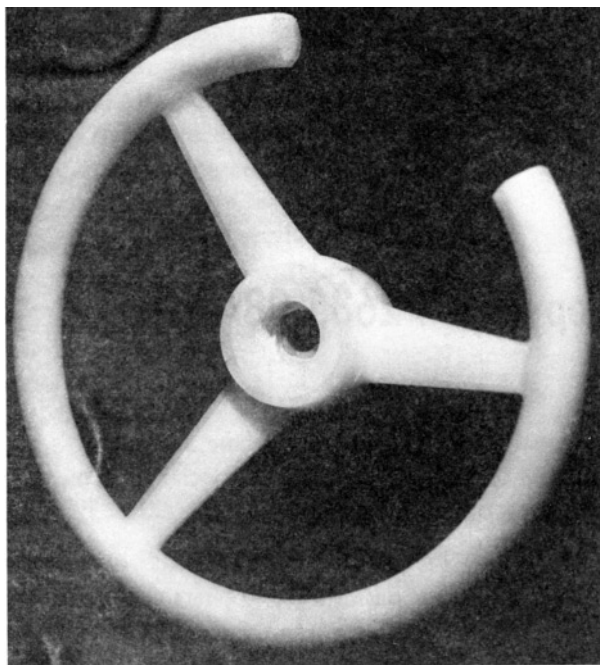


Figure 8.5 A steering wheel molded from a blend of 60% general purpose polypropylene and 40% foamable polypropylene (Tenite, Eastman Plastics). Molding conditions were: cycle time 35 seconds; melt temperature 193°C (380°F); mold temperature 4.4°C (40°F). [727]

Table 8.3 Typical Mechanical Properties of Parts Made with 100% Foamable Polypropylene^{1,2}

Property	ASTM Method	Value	
		Molding A	Molding B
Specific Gravity	D 792	0.7	0.5
Thickness, in. (mm)		¼ (6)	½ (12)
Deformation under 1000 psi (6.9 MPa) load at 122°F (50°C), %	D 621	10	25
Plaque Impact Strength, ft-lb (J)		3.0 (4.1)	4.5 (6.1)
Compressive Loading, psi (MPa) to cause 1% Deformation 10% Deformation	D 695	295 (2.0) 2565 (17.7)	180 (1.2) 1200 (8.3)
Flexural Modulus, 10 ⁵ psi (MPa)	D790	1.9 (1310)	-
Flexural Strength, psi (MPa)	D790	5484 (37.8)	-
Izod Impact Strength, ft-lb (J/m) Notched Unnotched	D256	0.4 (21) 6.1 (326)	-

¹ Molding conditions:

melt temperature of 190–219°C (375–425°F), with rear zone 11°C (20°F) lower than front

mold temperature — tap water or colder

no drying

fast fill rate

high injection pressure

low holding pressure

no back pressure except for shot capacity extension or color dispersion

² P2635–08AA, Eastman Plastics**Table 8.4** Mold Shrinkage of Parts Made with Foamable Polypropylene¹

Part	Materials	Specific Gravity	Mold Shrinkage, Mils/in. (mm/mm)
Impact Bar 1/4 in. (6.4 mm)	100% GPP ²	0.90	14–18 (0.014–0.018)
	50% GPP, 50% FPP ³	0.80	23 (0.023)
	100% FPP	0.75	24 (0.024)
Plaque (Sprue Gated) 5 in. x 5 in. x ¼ in. (127 mm x 127 mm x 6.4 mm)	50% GPP, 50% FPP	0.79	23 (0.023)
	50% GPP, 50% FPP	0.75	29 (0.029)
	100% FPP	0.79	22 (0.022)
	100% FPP	0.71	23 (0.023)
	100% FPP	0.63	24 (0.024)
Plaque (Sprue Gated) 5 in. x 5 in. x 1/2 in. (127 mm x 127 mm x 12.7 mm)	50% GPP, 50% FPP	0.76	27 (0.027)
	50% GPP, 50% FPP	0.67	27 (0.027)
	50% GPP, 50% FPP	0.60	25 (0.025)
	100% FPP	0.76	24 (0.024)
	100% FPP	0.65	22 (0.022)
	100% FPP	0.47	25 (0.025)

¹ Tenite polypropylene P2635–08AA (Eastman Plastics)² GPP = general purpose polypropylene³ FPP = Tenite polypropylene P2635–08AA

Modern plastic products are not biodegradable. Although most pure polymers degrade quite rapidly under environmental conditions of heat, light, and exposure to moisture and chemicals, modern plastic products are designed and chemically stabilized for a long service life. Some plastic products are recycled or incinerated; however, most are disposed of in landfills. Due to a high volume to weight ratio, plastics have become one of the most visible forms of waste to society, and the public regards plastic as the principal cause of the increased amount of garbage in landfills. Plastics, however, make up only 21% of the volume of all solid waste and 9 % of the weight, according to Environmental Protection Agency (EPA) statistics. [912, 182, 938]

Pressure for plastics recycling began in the 1980's due to a lack of landfill space in major cities and the increased cost of landfill disposal. In 1994, the amount of plastics recycled in Europe represented 6.4% of post-consumer waste. Large amounts of low density and linear low density polyethylene (LD/LLDPE) and high density polyethylene (HDPE; Figure 9.1) are recycled; since film, crates, and bottles are made primarily from these materials (films from LD/LLDPE and bottles and crates from HDPE), little material separation is necessary. [908, 913]

Polypropylene is used in many diverse applications and is not as easily recycled due to the necessity of material separation; about 14% of poly-

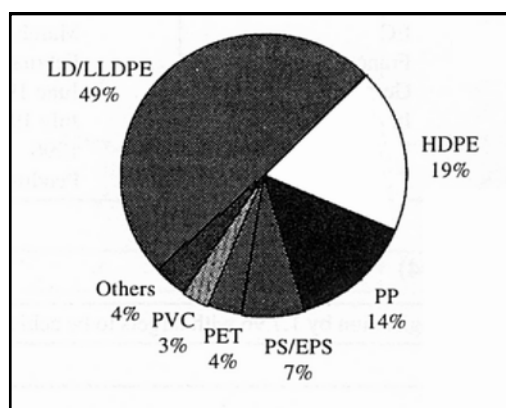


Figure 9.1 Recycling of post consumer waste plastic in Europe in 1994. Low density and linear low density polyethylene (LD/LLDPE) were recycled in the greatest amounts, due to their use as the primary materials in plastic films, followed by high density polyethylene (HDPE), used in bottles and crates. Polypropylene is used in many diverse applications, so that material separation is necessary; as a result, a lower percentage is recycled. [908]

propylene was recycled in Europe in 1994. Lead batteries with polypropylene cases have always been recycled on a large scale in order to recover the lead. Lead content has decreased, however, and the primary reason for battery recycling has changed to recovery of the polypropylene. Woven sacks, carpet backing, and strapping tape are also heavily recycled, due to the low amount of material separation required; a major application of recycled polypropylene from fibers is in plant pots. Other applications require collection and separation from different types of applications, and efficient recycling is not feasible. [908, 913]

Different recycling or waste disposal methods are shown in Figure 9.2 and described below. Mechanical recycling is the most common method; however, feedstock recycling and energy recovery are being investigated as alternatives due to contamination problems with mechanical recycling. [654]

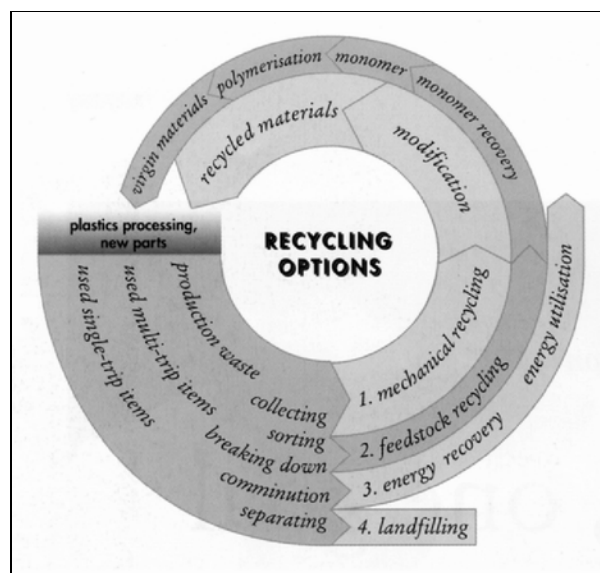


Figure 9.2 Types of recycling. In mechanical recycling, waste material is separated, remelted, and regranulated for use in new consumer products. Mechanical recycling requires separation of incompatible polymers to achieve good performance properties in the recycled product. In feedstock recycling, polymers are broken down into their constituent monomers or converted to synthetic oil or gases for use in other processes. Monomers can then be used to produce new virgin polymers. Energy recovery uses incineration of polymers to produce heat or energy. The final destination for most waste material, that is either not recycled or after many recycling cycles, is landfilling. [654]

9.1 Mechanical recycling

In material or mechanical recycling, waste material is collected, separated, cleaned, shredded, melted, and regranulated for use in new consumer products. The original material remains largely unchanged in its consistency, and the polymeric structure is retained. Mechanical recycling is useful when large numbers of plastic components are available from a single type of plastic, such as LDPE films, in order to avoid the large cost of separation. The diversity of plastic applications make mechanical recycling difficult and expensive, and the price of the recycled product is usually higher than that of the product made from virgin material. Recycled resins are frequently slightly higher in price than virgin resins, and recycled resins often fail to receive approval for some applications, such as those involving food contact. [654, 909, 182]

Separation of plastics into substantially single-variety fractions is usually necessary in order to produce high quality recycled resins. If used plastics are not separated, the different properties of the mixed polymers can have a mutually adverse effect, resulting in a recycled product of low quality. Contaminated or mixed plastics can be recycled, but the low quality limits the applications of the resulting product. Separation methods take advantage of the density and electrostatic differences between polymers. Low density polyolefins (polyethylene and polypropylene) are separated from higher-density materials such as polyvinyl chloride, polystyrene or polyethylene terephthalate using a hydrocyclone, a type of centrifuge, or a float/sink tank. The high density polymers can then be separated further using electrostatic processing methods that exploit the differences in electrical charge capacities of the polymers. [182, 654, 706, 913]

Some polymers may be reprocessed together for recycling using compatibilizers. Compatibilizers allow polymers that are not mutually miscible to form a homogeneous compound with good mechanical properties. Compatibilizers include

RCM 2 (BASF), used in recycling mixtures of polystyrene and polypropylene waste material, and RCM 3 (BASF), used to recycle blends of polypropylene and acrylonitrile/butadiene/styrene copolymers from automobiles into other automobile products. [182]

Performance deficiencies of recycled resins can be due to contamination, an unknown content of other resins or additives from the first life cycle, molecular weight and distribution changes resulting in melt flow and strength changes, and color. Metal particles remaining even after separation and cleaning can cause degradation and physical mixing problems, and the multiple heat cycles used in recycling processes can negatively affect melt flow and melt strength. The use of additives, possibly at a higher loading level to compensate for polymer degradation, provide more consistent properties. In addition to compatibilizers, coupling agents can aid in forming a homogeneous polymer mixture. Other useful additives include antioxidants, metal deactivators, heat stabilizers, impact modifiers, and viscosity enhancers. [909]

Recycled resins or regrind are frequently combined with virgin material to produce parts with performance properties matching that of the pure virgin material. Hoechst blends polypropylene from automobile bumpers and battery casings with virgin polypropylene, adding property-enhancing stabilizers and other additives to form high-quality polypropylene granules (Figure 9.3). The recycled resins, such as Hostalen PP 3100, are used as battery casing covers, mudguard linings, in the

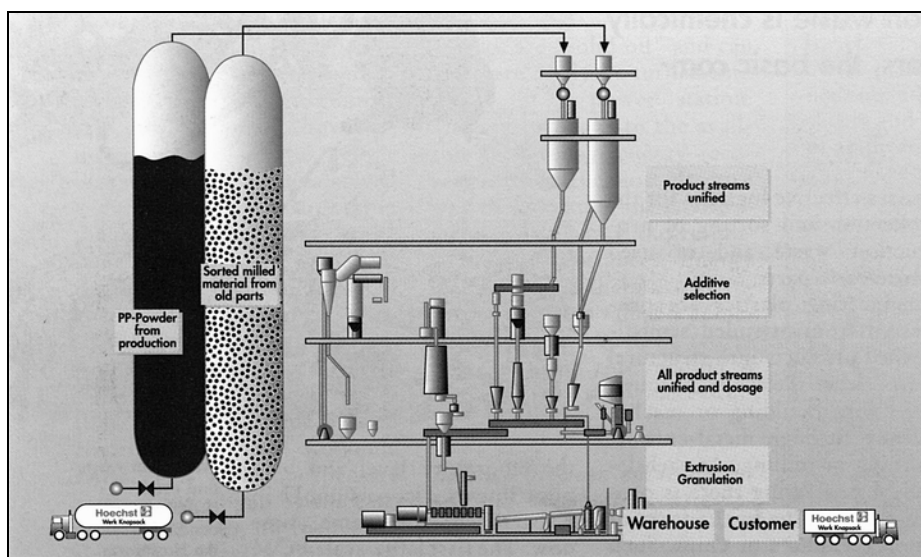


Figure 9.3 Diagram of the polypropylene recycling process at Hoechst. Virgin polypropylene is combined with various amounts of sorted, milled regrind. This blend is then combined with the appropriate additives and processed into products. [654]

wheelarches of the VW Polo, Seat Ibiza and Cordoba, Ford Mondeo, and Nissan models, as storage trays and footrests in the Honda, and in thrust rod covers in the Mercedes. The resin has very good impact strength, even at low temperatures, and good flowability, and it is suitable for injection molding. [910, 704, 706]

Another application of recycled polypropylene resins is in the injection molding of industrial components. Glass fiber reinforced polypropylene for this application is produced by BASF from recycled glass mat-reinforced polypropylene used in automotive components (load distributors, seat pans, engine compartment cladding, and brackets). Glass mat-reinforced polypropylene can withstand high mechanical and thermal stress, but damage to the glass fiber/matrix adhesion during the recycling process results in a sharp drop in mechanical strength. The waste material is cleaned and dried, treated with additives, and regranulated on a twin-screw extruder with vacuum devolatilization. The resin has very good flow properties, producing parts with good strength and high heat resistance. [182]

9.2 Feedstock recycling

In raw material or feedstock recycling, polymers are broken down into their constituent monomers or into liquid or gaseous hydrocarbons. Polycondensates, such as polyamide, polyurethane, and polyethylene terephthalate, are decomposed to monomers by hydrolysis or alcoholysis. Olefinic polymers, such as polypropylene, polyethylene, and polystyrene, are converted into petrochemical feedstocks by pyrolysis — coking (heating in the absence of air) or hydrogenation (heating in the presence of catalysts in a hydrogen atmosphere — or gasification (heating in the presence of oxygen). Pyrolysis is conducted in an inert atmosphere to prevent combustion of the hydrocarbons, and a mixed hydrocarbon oil and some synthetic gas is formed. Products from coking and hydrogenation can be reprocessed in a refinery and used as starting material for plastic production. Gasification produces a gas mixture useful in processes such as the production of methanol. [182, 654, 915]

Feedstock recycling is now becoming economically feasible as an alternative to conventional mechanical recycling. It can accommodate mixed plastics and produces crude oil or monomers with properties similar to virgin materials. [914, 654]

9.3 Thermal recycling

In thermal recycling or incineration, mixed plastic waste undergoes controlled combustion. The heat produced can then be used as substitutes for oil, gas, and coal or to generate energy at power plants (energy recovery). Plastic parts have about the same energy value as the oil from which they were produced — one ton of plastic has about the same energy value as one ton of oil — and thermal recycling can be used to reduce the use of fossil fuels for energy generation. Incineration is widely used in Japan as a method of waste disposal, with about half of the heat produced used for energy recovery. [182, 908, 654]

The high caloric value of plastics yields a high energy recovery, and incineration provides a secondary use of the material. Polypropylene burns to form the usual products of combustion, carbon dioxide and water. To achieve economic benefits, waste-to-energy facilities must be of a relatively large size, burning large amounts of mixtures of polymers. Arguments against incineration include the production of toxic and corrosive substances (dioxane and hydrochloric acid) by the incineration of polyvinyl chloride, although the amount produced is low. Ash residue from incineration must still be landfilled, although it is inert and comprises only a fraction of the volume of the original plastic material. [913, 915, 731]

9.4 Design for recycling

Problems of plastic waste generation are now being taken into consideration at the design stage of product development. In design for recycling, the suitability of a product design for recycling is considered, with products designed for easy disassembly and the use of compatible resins in material selection. New process technologies make possible the use of recycled resins in plastic parts. For example, in two component or sandwich molding, two shot molding, and coextrusion for profile and blow molding, two materials are combined in a component part. The second layer can be used as an outlet for recycled materials, while the other layer (skin, second shot, outer layer) uses virgin materials for cosmetic or property requirements of the application. [494, 916]

Life cycle analyses, in which all operations — beginning with raw material extraction, through processing and product use, and ending with dis-

posal — provide a way to view the environmental efficiency of consumer products. Stages of life cycle analysis consist of: inventory, which provides a detailed description of raw material input and waste output; interpretation, which links inventory results to identifiable environmental problems; and improvement, in which the system is modified to reduce environmental impact. [914, 494]

Design for recycling is a goal of the automobile industry, which is developing vehicles that are easy to dismantle and that indicate constituent

materials on components, allowing for easier material separation. Due to the versatility of polypropylene, it can be used in “unitary systems” for vehicle interiors, in which the number of different materials used is reduced. The Volvo S40/V40 uses significantly more polypropylene in its vehicle interior, reducing the number of different types of materials used from twelve in the earlier 400 series to six in the S40/V40. Polypropylene achieved very good results compared with other thermoplastics in life cycle analyses. [706]

Polypropylene resin without any additives is classified by the International Agency for Research on Cancer (IARC) in Group 3, “not classifiable as carcinogens”. Although polypropylene alone is not hazardous to health, polypropylene processing can release volatile organic compounds (VOCs) into the surrounding air, and residual monomers and catalysts present in the formulation increase the toxicity of the resin. These substances can migrate into food products through the plastic packaging or can migrate into the body from medical devices. Flame retardants decrease damage and death from fires but may also increase smoke generation and the evolution of toxic gases during a fire. Resins used in many applications must conform to regulations intended to protect the health and safety of the user.

10.1 Hazardous substances

10.1.1 Polypropylene

In studies of unstabilized polypropylene given to white mice (5–15 g/kg), the polymer was not found to be toxic, although some studies indicated pathomorphological changes in the liver, kidneys, and myocardium in mice killed two weeks after administration. Aqueous polypropylene extracts (20 and 60°C; 10 days) given over a period of 15 months produced small increases in body weight, conditioned reflexes, and mass coefficients of the liver and a reduced ability to produce antibodies. [949]

10.1.2 Propylene

Propylene monomer produced no toxic effects in white rats, either acute (administration of 0.5 ml of a 340 mg/L solution) or chronic (0.05 mg/kg over a period of six months). Chemobiokinetic studies indicate that propylene is removed rapidly through the lungs with no chemical changes. The IARC has no data on the carcinogenicity of propylene; other studies have found no carcinogenic effect in mice or rats after inhalation of 8.6 and 17.2 mg/m³. Propylene does not alter the color or transparency of water but does affect the odor of water above a concentration of 0.5 mg/L. [949]

10.1.3 VOC emissions

Plastics processing is a primary source of emission of volatile organic compounds (VOCs), according to the US Environmental Protection Agency, producing over 60 billion lbs/year. Polymers or additives present in the hot melt can form gaseous decomposition products, and organic solvents used in processing can become gaseous when exposed to high processing temperatures. In the USA, processors must report amounts of VOC emissions to state or local governments as part of a permit application for continued operation. [941, 186, 958]

Workers can be exposed to processing fumes or airborne organic solvents (which also represent a risk of fire) through inhalation or skin contact. Good ventilation, including exhaust fans on processing lines, can minimize exposure. In addition, melt overheating and the cleaning of machinery by flaming should be avoided. [941, 186]

A study of emissions from thermoplastics processing run by Rapra Technology Limited from 1991 to 1993 included polypropylene tape extrusion. In this study, static monitors (monitors not positioned directly on a worker) were used to test the atmosphere around the processing machinery (machine/operator monitors) and the general atmosphere of the workplace (background monitors). Background monitors were placed 4–6 m (13–20 ft) from processing machinery; machine monitors were placed 0.5 to 3 m (~1.5–10 ft) from processing machinery, in both upwind and downwind directions. Tenax and Chromosorb sorbent tubes were used to collect VOC samples; Tenax is recommended as a general purpose absorbent, while Chromosorb is useful for more volatile compounds. The contents of the sorbent tubes were desorbed by heat and analyzed by gas chromatography — mass spectrometry (GC-MS). [940]

The results obtained for polypropylene tape extrusion are given in Tables 10.1 and 10.2; occupational exposure limits for these substances, where available, are given in Table 10.3. A perceptible draught was present in the processing vicinity. The background atmosphere was monitored both during processing and machine purging. VOCs observed

Table 10.1 Fumes Emitted during Tape Extrusion of Polypropylene (Tenax absorbent) ¹

Compound	Concentration (mg/m ³)				
	Tube 1*	Tube 2*	Tube 3*	Tube 4*	Tube 5*
hydrocarbon (~C ₅ -C ₇)	0.48	0.22	1.65	0.27	0.23
hydrocarbon (~C ₆ -C ₈)	0.37	0.74	0.35	<0.1	<0.1
hydrocarbon (~C ₇ -C ₉)	0.58	0.46	1.79	1.05	0.79
hydrocarbon (~C ₈ -C ₁₀)	0.73	0.67	2.98	0.32	0.17
hydrocarbon (~C ₉ -C ₁₁)	1.49	1.04	5.24	<0.1	0.23
hydrocarbon (~C ₁₀ -C ₁₂)	0.89	0.44	2.68	<0.1	0.14
hydrocarbon (~C ₁₁ -C ₁₃)	1.43	0.97	5.38	<0.1	0.87
hydrocarbon (~C ₁₂ -C ₁₄)	2.27	0.15	6.69	<0.1	0.23
hydrocarbon (~C ₁₃ -C ₁₅)	0.88	0.52	1.70	<0.1	<0.1
xylene isomers	0.37	Not detected	Not detected	<0.1	<0.1
α-methyl styrene	0.16	<0.1	Not detected	0.11	Not detected

* Tube 1: Background
Tube 2: Machine/Operator, upwind side of die
Tube 3: Machine/Operator, downwind side of die
All monitors placed 1.5 m from floor
Machine/Operator monitors: 0.5–3 m from processing machinery
Melt temperature: 240°C (464°F)

Tube 4: Machine/Operator, purging
Tube 5: Background, purging

Background monitors: 4–6 m from processing machinery

¹ Tenax absorbent tubes analyzed after desorption by GC-MS

Table 10.2 Fumes Emitted during Tape Extrusion of Polypropylene (Chromosorb absorbent)

Compound	Concentration (mg/m ³)				
	Tube 1*	Tube 2*	Tube 3*	Tube 4*	Tube 5*
hydrocarbon (~C5-C7)	<0.1	0.15	0.57	<0.1	0.25
hydrocarbon (~C6-C8)	<0.1	0.32	2.16	0.47	0.55
hydrocarbon (~C7-C9)	0.17	0.58	0.92	<0.1	<0.1
hydrocarbon (~C8-C10)	<0.1	0.44	0.66	<0.1	0.66
hydrocarbon (~C9-C11)	<0.1	1.11	2.63	<0.1	2.45
hydrocarbon (~C10-C12)	<0.1	0.14	1.27	<0.1	0.36
hydrocarbon (~C11-C13)	<0.1	0.12	0.25	<0.1	1.09
hydrocarbon (~C12-C15)	0.11	0.10	<0.1	<0.1	1.56
xylene isomers	0.14	0.14	Not detected	Not detected	<0.1
benzene, alkyl derivative	<0.1	<0.1	Not detected	Not detected	0.40
α-methyl styrene	Not detected	<0.1	Not detected	<0.1	0.10

* Tube 1: Background
Tube 2: Machine/Operator, upwind side of die
Tube 3: Machine/Operator, downwind side of die
All monitors placed 1.5 m from floor
Machine/Operator monitors: 0.5–3 m from processing machinery
Melt temperature: 240°C (464°F)

Tube 4: Machine/Operator, purging
Tube 5: Background, purging

Background monitors: 4–6 m from processing machinery

¹ Chromosorb absorbent tubes analyzed after desorption by GC-MS

were mostly aromatic (xylene, methyl styrene, benzene) and aliphatic hydrocarbons; downwind levels were significantly higher than those found upwind of the processing machinery. [940]

10.1.4 Additives

The addition of additives to polypropylene can significantly increase the toxicity of the resin. Many additives require special handling to avoid worker

Table 10.3 Occupational Exposure Limits (USA) for Selected Compounds

Compound	Threshold Limit Values (mg/m ³)	
	TWA ¹	STEL ²
pentane (C ₅ — all isomers)	1770	2210
n-hexane (C ₆ isomer)	176	-
C ₆ (all isomers except n-hexane)	1760	3500
n-heptane (C ₇ isomer)	1640	2050
octane	1440	1750
nonane (C ₉ — all isomers)	1050	-
α-methyl styrene	242	483
benzene	32	-
xylene (all isomers)	434	651
¹ TWA = threshold weighted average, 8 hour reference period ² STEL = short term exposure limit, 15 minute reference period Limits issued by the American Conference of Governmental Industrial Hygienists (ACGIH)		

exposure to dust or fumes, and the toxicity of many additives pose waste disposal and environmental problems. Some additives can decompose at polypropylene processing temperatures, producing potentially toxic degradation products. Detailed information about the toxicity and hazards of specific additives can be found in the Material Safety Data Sheets (MSDS), available from the manufacturer; an MSDS for polypropylene is given in Figure 14.1. Some information can also be found in chemical reference books, such as the *Merck Index*. [943]

Many peroxides are skin irritants and are supplied in paste or bond form to reduce atmospheric contamination. Azocarbonamide blowing agents (ABFA) and related decomposition products are of low toxicity but cause skin irritation upon contact and respiratory problems if inhaled. Use in the form of a paste or polymer-bound masterbatch or dispersion helps minimize any toxic effects. [943]

Long term exposure of workers to mineral wool or fine diameter glass fibers has been correlated with higher rates of lung cancer. Fibrous materials, such as asbestos, have long been implicated in lung diseases. Although previous theories ascribed asbestos toxicity to chemical reactions of the fibers, the current view is that the hazards associated with asbestos fibers are due to particle size; if true, then any mineral fiber of the proper particle size would be hazardous. [943]

Sales of cadmium- and lead-based pigments have decreased due to the toxicity of heavy metals,

especially lead and cadmium. Sales of cadmium in 1995 were estimated at about 1/8 levels of 1990 sales, and sales of lead-based pigments have decreased 5–7%/year. Heavy metals are used for bright colors (red and yellow); use of low dusting formulations can help minimize health problems. Alternative colorants include formulations with mixed metal oxides, nickel and chrome titanates, and new organic pigments. Alternative colorants can cost four to five times as much as heavy-metal-based pigments, however, especially for polypropylene, HDPE, and LDPE, and organic pigments can degrade at processing temperatures, forming potentially toxic degradation products. [943]

Heavy metal-based pigments used in degradable plastics also cause potential environmental and health problems. Degradable plastics, used in packaging applications, incorporate additives or “weak links” in the polymer chain that degrade the polymer after a particular amount of time (i.e. photodegradation occurs after three months, or the molecular weight is reduced to a level at which biodegradation can occur). With degradable plastics, heavy metals are deposited at the place at which decomposition occurs; if incinerated, high concentrations of heavy metals build up in incinerator ash. [943]

Many flame retardants increase smoke generation during combustion; in addition, they can release toxic gases during a fire. Halogen-containing flame retardants such as octabromodiphenyl ether can produce dioxins and benzofurans during combustion; alternative formulations with low halogen or halogen-free materials (silicones, phosphorus) have been developed. Antimony trioxide, a mineral flame retardant, is also being used less frequently due to hazards associated with dust inhalation; use of pellet or wetted forms can reduce dust exposure. [943]

10.2 Potable water

The effect of polypropylene on potable water has been investigated due to its use in containers for aqueous solutions in foods and medicines and in pipes used in carrying drinking water. Organoleptic qualities may be affected, and components may migrate into water from the resin. Standard conditions for aqueous extracts in potable water tests are a specific surface of 1 cm⁻¹, temperatures of 20 and 37°C (68 or 98.6°F), and a time of exposure of 24 hours; aggravated testing conditions include greater exposure times or specific surfaces or

higher temperatures. Specific surface is the ratio of the surface area of the polymer (in cm²) to the volume of liquid in contact with it (in cm³). [949]

In studies of aqueous extracts, there was no significant effect on organoleptic qualities. Small amounts of component migration into extracts was observed; results of one study are given in Table 10.4. The intensity of migration of organic and brominating compounds was inversely proportional to the melt flow index and to the atactic content of the polymer. [949]

Standard aqueous extracts of polypropylene (“Propatene” grade, with 3% SAO–6, 0.3% di-lauryl-3,3’-thiodipropionate (DLTDP), 0.5% Tinuvin) used in the production of filters for artesian wells displayed no off-taste or odor but did contain some organic substances. After an exposure time of 10 days, the oxidizability of the extracts increased by 0.16–0.24 mg/L O₂; no unsaturated compounds of low molecular weight (such as formaldehyde) were present. A small increase in oxidizability at long exposure times and higher temperatures was also found in aqueous extracts of polypropylene (stabilized with DLTDP, Topanol SA, benzone OA, and calcium stearate) used in the manufacture of immersion pumps; organoleptic qualities of the water were unchanged. [949]

In other experiments, water from pipes composed of polypropylene stabilized with carbon black and an antioxidant (SAO–5) acquired an odor and taste that was retained for up to 13 pours. In aqueous extracts of polypropylene stabilized with Irganox 1010 and calcium stearate, no brominating compounds, catalyst residues (titanium), stabilizers, or formaldehyde were found, although traces of butanol and hexane were detected in some samples. [949]

Table 10.4 Component migration from polypropylene into aqueous extracts¹

Component	Concentration	
	20°C	60°C
Organic substances	1.8 mg/L O ₂	
Brominating substances ²	1.2 mg Br ₂ /L	
Isopropyl alcohol	0.5 mg/L	4.5 mg/L
Methyl alcohol		0.21 mg/L
Formaldehyde		0.013 mg/L

¹ Data was not available for all components at all temperatures
² Iodate oxidizability

10.3 Food Contact Applications

Plastic materials used for packaging come into direct contact with food. Plastic materials are not inert, and some interaction with the food substance can occur. Additives, monomers, catalyst residues, polymer degradation products, or residual polymerization solvents can migrate into the food in response to a concentration gradient; concentration of the substance in the food is lower than that in the packaging material. Interaction of food products with packaging can occur during preparation or storage and is affected by environmental conditions such as temperature and storage time. Migration can result in product toxicity or the formation of undesirable flavors or odors. [890]

10.3.1 US food packaging regulations

In the US, preclearance by the Food and Drug Administration (FDA) is required for materials in contact with food. Resins and additives are considered indirect additives and must be tested with food simulants to determine the amount of extractables. Examples of food simulants include distilled water (for aqueous foods of pH <5), vegetable oil (for fatty foods), and 3% acetic acid (for aqueous acidic foods of pH >5). Toxicity testing must then be performed on the extracted components. Results, along with proposals for regulation of the indirect additive, are submitted to the FDA for approval. FDA regulations of the approved additive, which specifies how the new additive can be used in food contact applications, is published in the Federal Register. [957, 944]

10.3.2 Canadian food packaging regulations

Food packaging materials in Canada are not considered additives and do not require preclearance. Division 23 of the Food and Drug Regulations prohibits the sale of foods in packages that may impart harmful substance to the food and makes the food seller responsible for the safety of packaging materials. As a result, food suppliers generally require assurance from packaging suppliers that the materials used are safe for food applications. [944]

To identify materials that are likely to be acceptable under Division 23, The Health Protection Branch of the Health and Welfare Department issues a letter of no objection to materials that do not pose a health risk. There are no specific regulations specifying lists of permitted ingredients. Packaging manufacturers submit information regarding the identity of the product, the proposed use of the

packaging material, the components likely to be extracted into foods, and toxicological data on the extractable constituents. Toxicological data is not required on components if the probable daily intake is estimated as less than 25 ng/kg body weight, using the prescribed calculations. [944]

No objection letters specifically identify the product and state that there is no objection to specified food contact end uses, based on the submitted information and provided that the material is technically suitable for the application. The no objection letter can then be presented to potential customers. [944]

10.3.3 European food packaging regulations

In the European Union, Directives have been established to ensure that food contact materials do not transfer any constituents to foods in quantities that could endanger human health. A positive list approach is used, in which all substances permitted in food contact materials must be listed, along with the identity of the material and any restrictions. Substances that are not on the list cannot be used in food contact applications. [956]

For new food contact materials to be included in the list, migration testing studies must be completed. Materials must adhere to both overall migration limits (OM) and one or more specific migration limits (SML); testing must be performed in all food simulants, unless food contact use will be restricted. The overall migration limit is the total amount of migration allowed from the packaging material. It is set at 10 mg/dm² of surface area of the material or at 60 mg/kg foodstuff for containers between 500 mL and 10 L, in which surface area measurement is impractical, and for caps, gaskets, stoppers, or other sealing devices. The OM is a measure of the inertness of the packaging material and is designed to minimize food contamination; it has no toxicological basis. [890, 956]

The specific migration limit is substance-specific and must be complied with in all food simulants. It is toxicologically based on mutagenicity studies and on in vivo animal studies. The amount of toxicity testing required is based on the calculated migration of the specific substance from the packaging into the food or food simulant, ranging from mutagenicity studies in bacterial or mammalian cell systems (<50 ppb migration) to “core” data that includes carcinogenicity, teratogenicity, and adsorption/excretion studies (>5 to <60 ppm). An SML is assigned for the substance

based on a person who weighs 60 kg (132 lb) and who consumes 1 kg (2.2 lb) of food packaged in plastic per day and assumes that the packaging contains all substances at maximum permissible limits. [956, 890]

10.4 Medical Devices

New medical devices must usually undergo thorough biocompatibility testing by the manufacturer in order to meet regulatory requirements. Biocompatibility tests are designed to determine the risk of adverse health effects from either normal use or likely misuse of the medical device. The amount of testing necessary has increased in recent years. Acute testing following the FDA’s General Program Memorandum G95–1 (see below for a description of regulatory requirements) can cost \$6000 (US dollars) and require 90 days to complete; additional tests (subchronic, chronic, and carcinogenicity testing) increases costs by several thousand dollars. Biocompatibility testing has been carefully studied by the FDA in recent years due to problems with silicone breast implants, jaw implants, and Shiley heart valves, which were all approved through the 510(k) process, and new regulations, such as labeling requirements for latex-containing devices, are being proposed. [947, 953, 945, 809]

10.4.1 Migration of toxic substances

The toxicity of a medical device is strongly dependent on the toxicity of soluble components of the materials and the extent to which they migrate into the body. Potentially toxic substances include polymer additives (antioxidants, stabilizers, plasticizers), substances added during manufacturing (lubricants, mold release agents, cleaning agents), contaminants for manufacturing (metals, regrind, organic compounds), and products from polymer degradation during storage or after implantation of the device. [954, 953]

In-vitro cytotoxicity assays, in which the response of mammalian cells grown in a cell culture medium in an artificial environment (test tube, glass dish) to a substance is determined, are widely used in screening for the presence of toxic substances. These assays, in contrast to in-vivo animal tests, determine toxicity under conditions that involve limited or no dilution or metabolism of the substances, so that the cell dose is greater than that in most clinical applications. Most studies determine the toxic response of the cell to a

chemical mixture but do not specifically identify the toxic agent; some toxic substances released from plastics that have been identified are listed in Table 10.5. [948, 946]

Migration of extractable substances from a solid, polymeric medical device into body tissues or a culture medium is dependent on the physiochemical properties of the substance, such as molecular weight, ionic state, solubility, and polarity. Substances with an octanol-water partition coefficient (P_{ow}) of greater than 4 (water-insoluble) are less likely to migrate into aqueous bodily fluids than those with $P_{ow} < 4$ (water soluble). Most plastics are nonpolar and water-insoluble; extractable substances are usually low molecular weight additives and reaction products. [948]

Extraction occurs through partitioning of the substance between the two phases. Substances on the surface of the material are the first to partition into the culture medium; substances in the interior of the polymer must first migrate to the surface before partitioning can occur. The rate of extraction is dependent on conditions such as temperature and solvent; ISO 10993–12 generally recommends extraction at 37°C (98.6°F) for 24 hours for in vitro cytotoxicity tests. The extraction rate can be increased by procedures such as steam sterilization, which causes plasticizers and other additives to migrate to the polymer surface (“blooming”). [953, 948]

10.4.2 Regulatory guidelines

Regulatory guidelines for biocompatibility testing include the U.S. Pharmacopeia (USP) tests, in vivo biological reactivity tests with classes from I to VI,

Table 10.5 Some identified toxic substances in plastic medical devices

aluminum	lead
acrylonitrile monomer	mercaptobenzothiazole
arsenic	methylene dianiline
benzene	nickel
benzoic peroxide	pyrene
bisphenol A	tetramethylthiuram
cadmium	monosulfide
carbon tetrachloride	tetramethylthiuram
dibutyl tin	disulfide
ethylene dichloride	tricesyl phosphate
ethylene oxide	triphenyl phosphate
formaldehyde	vinyl chloride monomer
2-(2-hydroxyethylmercapto)benzothiazole	zinc dialkyldithiocarbamates (methyl, ethyl, butyl, ethylphenyl, and pentamethylene)

and the Tripartite document, issued in 1986 by the US, Canada, and the United Kingdom. Polypropylenes usually pass both the Class VI USP tests and the Tripartite tests without difficulty. Both have been replaced by guidelines from the International Organization for Standardization (ISO) in a step toward international harmonization of requirements. [693, 953]

ISO 10993, *Biological Evaluation of Medical Devices*, outlines methods for evaluating the safety of medical devices that are directly or indirectly in contact with the body or with bodily fluids. It is divided into 17 parts that have either been accepted as an international standard or that are under development (Table 10.6) dealing with different types of tests, sample preparation methods, and animal welfare requirements. [953]

In the ISO standard, the recommended biocompatibility testing is dependent on the use of the device, the type of tissue in contact with the device, and the duration of contact. Medical devices are divided into three categories, depending on the

Table 10.6 Parts of ISO 10993: Biological Evaluation of Medical Devices

Part	Title
1	Evaluation and Testing
2	Animal Welfare Requirements
3	Tests for Genotoxicity, Carcinogenicity, and Reproductive Toxicity
4	Selection of Tests for Interactions with Blood
5	Tests for Cytotoxicity — In Vitro Methods
6	Tests for Local Effects after Implantation
7	Ethylene Oxide Sterilization Residuals
8	Clinical Investigation of Medical Devices
9	Degradation of Materials Related to Biological Testing
10	Test for Irritation and Sensitization
11	Test for Systemic Toxicity
12	Sample Preparation and Reference Materials
13	Identification and Quantification of Degradation Products from Polymers
14	Identification and Quantification of Degradation Products from Ceramics
15	Identification and Quantification of Degradation Products from Coated and Uncoated Metals and Alloys
16	Toxicokinetic Study Design for Degradation Products and Leachables
17	Glutaraldehyde and Formaldehyde Residues in Industrially Sterilized Medical Devices

method of bodily contact: surface devices, externally communicating devices, and implant devices. Each category is divided into subcategories according to the type of contact — skin, mucous membranes, and breached or compromised surfaces for surface devices, blood path indirect, tissue/bone/dentin communicating, and circulating blood for externally communicating devices, and tissue/bone or blood for implant devices (Table

10.7). Suggested tests are listed for each type of contact, depending on the contact duration (limited (<24 hr.), prolonged (24 hr. to 30 days), permanent (>30 days)). [809. 953]

The ISO matrix of tests is a guide to biocompatibility testing and not a checklist. Materials that are shown to be identical in formulation, processing, and sterilization to a device already on the market may require little or no biocompatibility testing.

Table 10.7 ISO 10993–1 biocompatibility tests and FDA modifications

Device Categories	Body Contact	Contact Duration ¹	Biological Tests ²									
			CYT	SEN	IRR	AST	SCT	GEN	IMP	HEM	CHR	CAR
Surface devices	Skin	Limited	X	X	X							
		Prolonged	X	X	X							
		Permanent	X	X	X							
	Mucous membrane	Limited	X	X	X							
		Prolonged	X	X	X	*	*		*			
		Permanent	X	X	X	*	X	X	*		*	
	Breached or compromised surfaces	Limited	X	X	X	*						
		Prolonged	X	X	X	*	*		*			
		Permanent	X	X	X	*	X	X	*		*	
Externally communicating devices	Blood path indirect	Limited	X	X	X	X				X	X	
		Prolonged	X	X	X	X	*			X	X	
		Permanent	X	X	*	X	X	X	*	X	X	X
	Tissue/bone/dentin communicating ⁴	Limited	X	X	X	*						
		Prolonged	X	X	*	*	*	X	X			
		Permanent	X	X	*	*	*	X	X		*	X
	Circulating blood	Limited	X	X	X	X		* ³		X	X	
		Prolonged	X	X	X	X	*	X	*	X	X	
		Permanent	X	X	X	X	X	X	*	X	X	X
Implant devices	Tissue/bone	Limited	X	X	X	*						
		Prolonged	X	X	*	*	*	X	X			
		Permanent	X	X	*	*	*	X	X			X
	Blood	Limited	X	X	X	X			X	X	X	
		Prolonged	X	X	X	X	*	X	X	X	X	
		Permanent	X	X	X	X	X	X	X	X	X	X

* FDA test modifications to ISO 10993–1

¹ Limited = <24 hr. Prolonged = 24 hr. — 30 days Permanent = >30 days

² Key to Biological Tests:

CYT = cytotoxicity

SEN = sensitization

IRR = irritation/intracutaneous reactivity

AST = acute systemic toxicity

SCT = subchronic toxicity (subcutaneous toxicity)

GEN = genotoxicity

IMP = implantation

HEM = hemocompatibility

CHR = chronic toxicity

CAR = carcinogenic toxicity

³ FDA requires this test for all devices used in extracorporeal circuits

⁴ FDA includes tissue fluids and subcutaneous spaces in this category

Testing performed simply to satisfy requirements may result in overtesting, or an optional test that could identify an adverse health effect may be missed. For optimum use of the ISO standard, a toxicologist should consider the characterization of the material and historical data from similar devices to determine which tests should be performed. Contact with the certifying authority should be initiated before testing is begun and maintained throughout the process. [953, 947]

Beginning in 1998, all medical devices sold on the European Union market must comply with directive 93/42/EEC issued in 1993. The European Committee for Standardization (CEN) is now in the process of accepting ISO 10993 as the European standard. [953]

In the Blue Book Memorandum G95-1 (1995), the FDA accepted the ISO 10993-1 standard, with modifications in the testing matrix (Table 10.7); more testing is recommended for systemic toxicity, sub-chronic toxicity, and implantation than in the ISO standard. G95-1 emphasizes a case-by-case testing strategy, in contrast to the Tripartite standard, and assists in selecting toxicity tests for 510(k) devices. Required genotoxicity testing — for gene mutation, chromosomal aberrations, and effects on DNA — is greater than in the Tripartite document and has become more sophisticated, and there is an increased emphasis on analytical characterization of the materials, using methods such as infrared spectroscopy, chromatography of extracts, thermal analysis, and scanning electron microscopy. [954, 953]

Polypropylene is used in components of automobiles and large and small appliances, packaging films and containers, medical devices, and textiles. A good balance of properties, which can be tailored to a wide range of fabrication methods and applications, and its low cost make it useful in many different industries.

11.1 Automotive applications

Polypropylene is used throughout the automobile — in interiors, exteriors, and under-the-hood. It is used in the automobile industry more than any other single polymer, and its usage is increasing. In the Opel Astra, 68% of the thermoplastic components are composed of polypropylene, compared to 10% nylon, 6% ABS, 4% polyethylene, and 12% of other thermoplastics. In Ford models, use of polypropylene has increased from an average of 5.5 kg (12.1 lb) in 1980, to 8.0 kg (17.6 lb) in 1985, to 17.0 kg (37.4) in 1990. [923, 919]

Mineral- and glass-reinforced polypropylenes, polypropylene homopolymers and copolymers, thermoplastic vulcanizates, and polypropylene foams are used in applications ranging from struc-

tural components and energy absorbing media to interior trim, carpeting, and fluid containers. The wide use and versatility of polypropylene in automotive applications facilitates mechanical recycling, since less material separation is required, and the resin maintains good mechanical properties after reprocessing. [935, 920]

11.1.1 Exterior automotive applications

Automobile bumpers are commonly made using polypropylene. Plastic bumper systems generally consist of an inner beam, an energy absorbent core, and a fascia. Elastomer-modified, UV-stabilized polypropylenes, reinforced or unreinforced, and foamed grades are usually used in bumpers. Elastomer-modified grades in fascia provide a balance of toughness and rigidity in order to meet current regulations. Bumper fascia must have good rigidity and maximum impact resistance, even at low temperatures (Figures 11.1 and 11.2). [919, 910, 920]

Stampable glass mat reinforced (GMT) polypropylene homopolymer can be used in bumper beams, depending on the application. GMT is composed of continuous, unidirectional glass fibers that can be arranged in a particular direction to meet demanding performance requirements. In the Jaguar saloon, the bumper beam is used mainly as a carrier for the cosmetic cover; replacement of steel by GMT, appropriate for this application, can result in 30–40% weight savings and ~40% in tooling costs, and the cost of corrosion prevention is eliminated. [919, 910, 920]

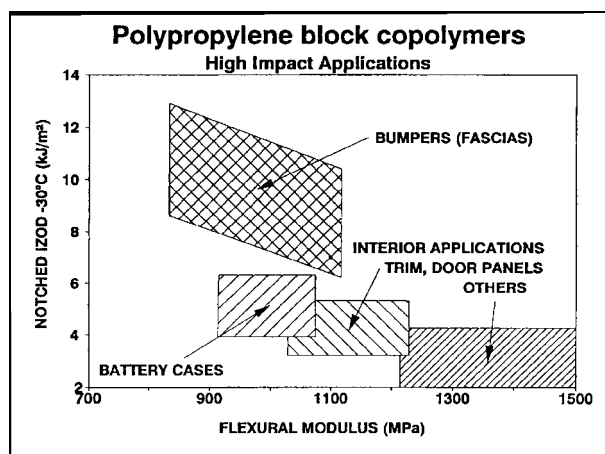


Figure 11.1 Rigidity and impact strength necessary for high impact automotive applications. Bumper fascia require good rigidity and maximum impact resistance; good rigidity and high impact resistance are necessary for battery cases. In interior applications, trim, door panels, and lower interior parts require rigidity and good impact resistance; rigid block copolymers are usually used. Dashboards, commonly made from blends of polypropylene/EPDM/talc, require rigidity, high heat deflection temperatures, and good impact resistance for sun-exposed parts. Parts in the upper half of the car interior, usually made from homopolymer or block copolymer and talc, require high rigidity (>3000 MPa; 435,110 psi). [920]

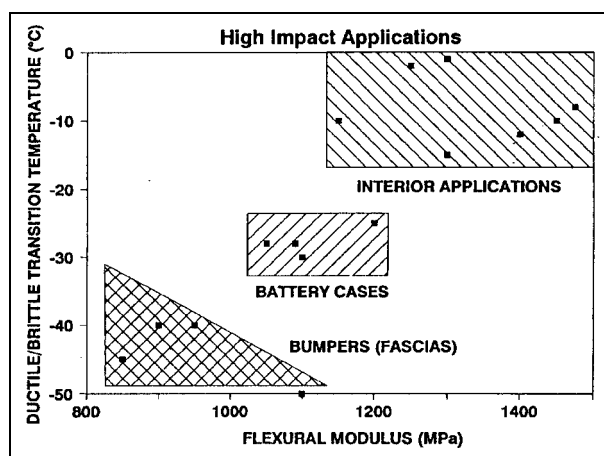


Figure 11.2 Impact resistance of automobile applications at low temperatures. Exterior bumper fascias require maximum impact resistance at low temperatures. A high level of impact strength is required for battery cases; for interior applications, low temperature impact resistance is not as critical. [920]



Figure 11.3 A bumper made from talc-reinforced, elastomer-modified polypropylene (Hostacom; Hoechst) [910]

Modern bumpers are integrated into the car body, painted the color of the car, and adjusted to fit the contours of the load-bearing structure. Primers are necessary to promote adhesion of the paint to the bumper surface, and a surface treatment such as flame treatment may be required. [919, 910, 920]

Automobile manufacturers that use polypropylene bumpers include Ford (Orion, Escort), Peugeot (405), Volvo, Opel, and BMW. Polypropylene/EPDM blends used in the Opel Omega provide impact resistance (at temperatures as low as -30° (-22°F)), UV resistance, high dimensional accuracy, a high-quality surface finish, and excellent weathering and chemical resistance properties. The bumpers are lightweight and easily painted, and special grades are available that result in low shrinkage, necessary when painted and unpainted bumpers are produced from the same injection mold. Resins have low thermal expansion (expansion coefficient $50\text{--}80 \times 10^{-6}\text{K}^{-1}$) in order to accommodate the small gaps (“zero-gap concept”) between the bumper and body parts present in modern automotive design. A polypropylene bumper is shown in Figure 11.3. [704, 910, 654]

Expanded polypropylene (EPP) foam is used in the bumper core on the 1997 Buick Park Avenue (Figure 11.4a). EPP is more resilient and is 30% lighter than other cushioning materials with the same performance properties. Due to a high ratio of impact strength to density, thinner walls can be used on the bumper cores, resulting in greater styling flexibility. Other uses of EPP foam in automotive applications are shown in Figure 11.4b. [899]

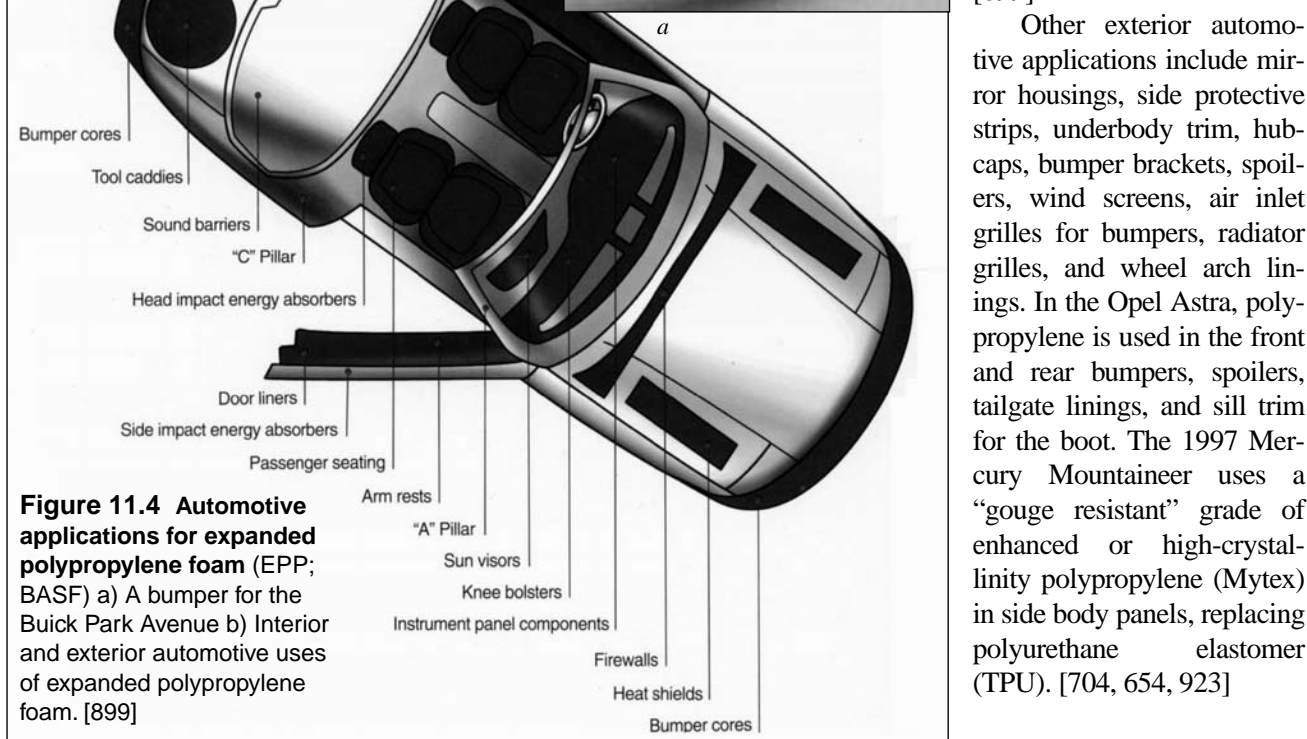


Figure 11.4 Automotive applications for expanded polypropylene foam (EPP; BASF) a) A bumper for the Buick Park Avenue b) Interior and exterior automotive uses of expanded polypropylene foam. [899]

Other exterior automotive applications include mirror housings, side protective strips, underbody trim, hubcaps, bumper brackets, spoilers, wind screens, air inlet grilles for bumpers, radiator grilles, and wheel arch linings. In the Opel Astra, polypropylene is used in the front and rear bumpers, spoilers, tailgate linings, and sill trim for the boot. The 1997 Mercury Mountaineer uses a “gouge resistant” grade of enhanced or high-crystallinity polypropylene (Mytex) in side body panels, replacing polyurethane elastomer (TPU). [704, 654, 923]



Figure 11.5 The side rubbing or protector strip on the Audi A4, produced from a polypropylene mineral-reinforced thermoplastic elastomer (Hostacom; Hoechst). The strip is painted to match the color of the car, and no metal insert is used. [704]

The Opel Omega uses a recyclable PP/EPDM thermoplastic elastomer for the side protective strip, which protects the doors from damage. The easy-flowing material is bonded to a galvanized steel profile and fixed to the car with double-sided adhesive tape. The resin has a low coefficient of thermal expansion and excellent weathering resistance. The Audi A4 uses a mineral-reinforced thermoplastic elastomer, with no metal insert, for the side rubbing strip (Figure 11.5). The painted strip is fixed to the car with adhesive tape. [704, 654, 923]

Polypropylene rear view mirror housings are used in the Renault Clio and Twingo and Peugeot 106. Rear view mirror housings require materials with adequate mechanical strength, even at low temperatures, resistance to cleaning agents and UV radiation, and the ability to withstand high winds and vibration. [654]

11.1.2 Interior automotive applications

Although performance requirements of interior trim components are less demanding than exterior applications, interior automotive components must also comply with aesthetic and safety requirements. Environmental aging tests subject the interior component to temperature extremes of -40°C (-40°F) to 75°C (167°F) for components below waist level and up to 105°C (221°F) for components in sunlight (above waist level), in addition to UV exposure and humidity; cracking, crazing, color changes, or other effects should not be apparent after testing. Other tests include color fastness, abrasion resistance, fluid resistance, and flammability. Components within a specific radius of the driver cannot break into pieces with sharp, jagged surfaces on impact, and the component should be aesthetically pleasing, with no rattles or squeaks during operation. [919]

Interior automotive applications generally use a talc-filled, impact-modified grade of polypropyl-

ene. Applications of polypropylene include door post cladding and pockets, air ducts, heater/air conditioning unit casings, armatures for fascia panels and centre consoles, and carpeting. Polypropylene is used for fascia panels on the Ford Fiesta and Escort and the Opel Vectra and has been used in instrument panels, consoles, quarter panels, and pillars in Chrysler, Ford, and GM vehicles since the early 1990s. [919, 895]

Polypropylene provides a good price to performance ratio, weight reduction, recyclability, improved acoustic damping compared to other polymers such as ABS, and reduced windscreen fogging. Windscreen fogging is generally due to migration of volatile components from the polymer resin. The low stiffness of polypropylene makes thicker, bulkier moldings necessary, so that direct replacement of other plastics is not possible without expensive tool and design modifications. [919, 895, 922]

Talc-filled polypropylenes generally have poor scratch resistance; however, coated grades are available that do not exhibit the usual white marks after flexing or scuffing. Marking occurs when mechanical damage to the surface disturbs the resin's surface layer, resulting in changes in light reflection and exposure of talc particles; whitening and increases in gloss occur in the affected area. Whitening is most noticeable on dark moldings or finely-textured surfaces; colors exhibit increased gloss. [919, 895, 922]

Volkswagen uses 20% talc-reinforced polypropylene for the pillar trim of the Polo (Figure 11.6). The material displays good flowability and retains toughness even at low temperatures. In the Opel Omega, the textile surface of the A-pillar is produced by backmolding the textile trim with mineral-reinforced polypropylene. Scratch-resistant



Figure 11.6 Pillar trim of the Volkswagen Polo, made with 20% talc-reinforced polypropylene (Hostacom; Hoechst). [654]



Figure 11.7 Fascia on the Opel Corsa, made from 40% mineral-reinforced polypropylene (Hostacom; Hoechst). [704]

grades are used in the central console of the Volvo S40/V40 (PP/EPDM), in the dashboard carrier and facing and the glovebox lid of the Mercedes Benz Sprinter (reinforced PP), and in the tailgate trim material on the Audi A4 (block copolymer). [654, 910, 704]

Other applications include fascia in the Opel Corsa and Tigra (Figure 11.7); tailgate and side trim, hand grips, door post trim, and the center console on the Opel Astra, and speaker housings in the Ford Mondeo and Fiesta (40% mineral-reinforced). The housing for the warning, control, and indicator lights for the Ford Mondeo are made from a white-colored grade of polypropylene due to good light-absorbing properties that shield the lights from each other. Polypropylene is being used to replace ABS, polyamide (PA), and polycarbonate (PC) due to its recyclability, rigidity, low warpage, and flowability. [654, 910, 923]

In the BMW 3 series, polypropylene is used in door handles (Figure 11.8), door pockets, and trim and parcel shelves. The resin provides a balanced rigidity/toughness ratio, good scratch resistance, low thermal expansion, sound-deadening properties, and recyclability. In Volvo trucks, polypropylene is used in the three-part center console with storage trays, A and B pillar trim, and door tread. Truck materials must withstand much harsher conditions than in cars, due to vehicle vibrations and increased driver use. The polypropylene components, designed for hard wear, deaden sound and vibrations, are UV-resistant, and have a touch-friendly finish. [704]

Cross-linked, foamed blends of polypropylene and polyethylene sheetstock are widely used in Japan as padding in car interiors in door trim panels, inserts, instrument panels, glove box doors, roof liners, pillars and seatbacks. Polypropylene contributes durability, high thermal stability, and mechanical stiffness, while polyethylene provides elongation, ductility, and softness. The blends, which are foamed after crosslinking, may provide a substitute for polyvinylchloride foams. [918]

Dashboards made entirely of polypropylene are being developed. Currently, most dashboards are a three-layer structure consisting of a glass-filled polypropylene beam, a polyurethane foam core, and a polyvinylchloride (PVC) skin cover. An example of an all-polypropylene dashboard includes a beam of talc-reinforced homopolymer or copolymer, a core of expanded polypropylene (BASF), and a rubber-modified block copolymer skin cover. Ferro is developing a foamable polypropylene with a small amount of metallocene polypropylene added for a softer feel and more flexibility and heat resistance in the dashboard core. [895, 922]

11.1.3 Under-the-hood automotive applications

The most severe environment in the automobile is the engine compartment; temperatures can range from -40°C (-40°F) to 140°C (280°F), and parts are exposed to vibrations and to chemical attack by lubricants and fuels. Heat resistance has become even more important in recent years due to the tendency of engine compartments to become more enclosed, causing higher temperatures. [923, 704]

The largest amount of polypropylene in under-the-hood applications is used for battery cases.



Figure 11.8 Polypropylene door handles on the BMW 3 series (Hostacom; Hoechst). [704]

Polymer properties required for battery cases include good rigidity and a high level of impact resistance, especially at low temperatures (Figures 11.1 and 11.2). Other applications include fluid reservoirs (water, antifreeze, brake fluid, etc.), headlamp housings, air ducts, fans and brackets, fan wheels, air filter housings, charcoal canisters, radiator frames, steering rod covers, cable ducts, timing chain covers, heater housings, and central electric housings. GMT materials are used in semi-structural applications such as battery trays, engine shields, support panels for radiator and fan housings; polypropylene, PBT, or PC/PBT is used, depending on the heat resistance required for the component. [924, 920, 923]

In the Mercedes Benz E class, reinforced polypropylene is used in the radiator frame, the air intake grille, the radiator tank cover, the housing of the central electrical components, the lid of the cooling water compensation reservoir, the heating and ventilation housings, and the headlight housings. Headlight

housings are generally made from talc- and glass fiber-reinforced grades and have high dimensional stability, good heat resistance and low temperature stability, good processability, and good chemical resistance. Due to their toughness, the housings can be installed by snapfitting, making dismantling and recycling easier. [704, 910]

Heater housings for the Mercedes C class are made of 40% mineral-reinforced polypropylene. Use of this material has reduced fogging and eliminated the unpleasant odor that entered new car interiors along with the heated air. The housing is dimensionally and heat stable and reduces transmission of structural-borne sound. [704]

Polypropylene used in ventilation grilles exhibits good weathering resistance, and the grilles retain their visual appearance even after several years. The polypropylene spoiler on the Peugeot 406 remains UV resistant and dimensionally stable under severe heat; in addition, the good flowability of the resin makes production easier. The Opel

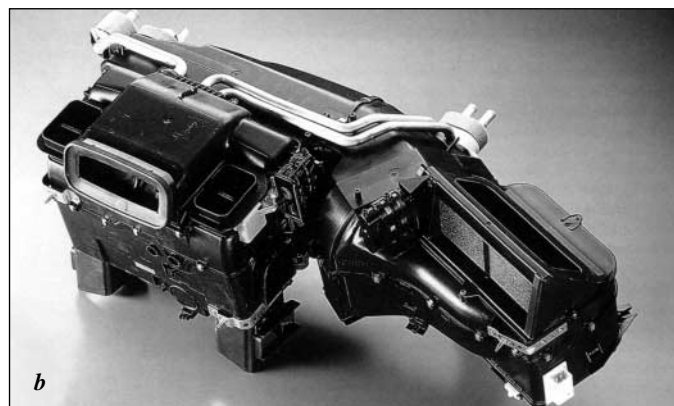
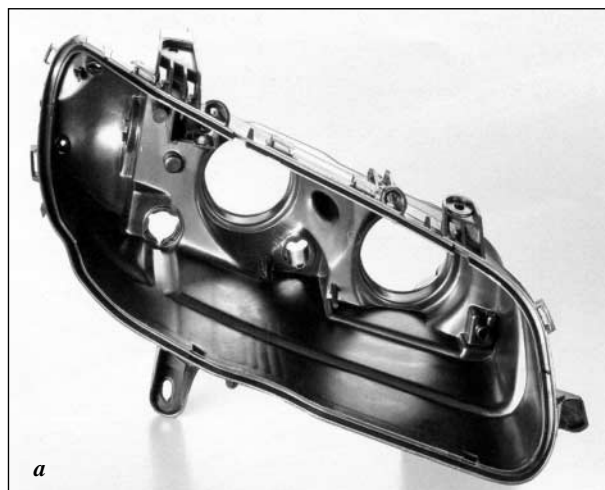
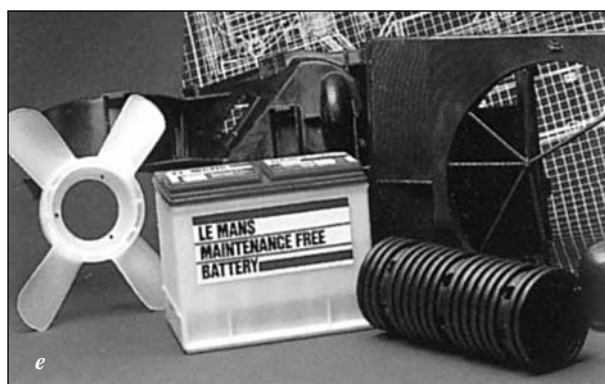


Figure 11.9 Under-the-hood applications of polypropylene (a – d made from Hostacom from Hoechst; e from Amoco) a) headlight housing b) heater housing c) ventilation grid d) draft deflector e) battery case, fan [910, 718]



Astra uses polypropylene in air cleaner housings, air ducts, coolant, washer, and brake fluid reservoirs, battery casings, and fan mounts. Two-part polypropylene structural ducts in the 1997 Ford Flareside truck replaced ABS, resulting in lower cost and improved sound-deadening properties. The ducts can be hot plate welded. Several under-the-hood applications of polypropylene are shown in Figure 11.9. [910, 923, 895]

11.2 Medical Applications

Polypropylene is used in a variety of medical applications — medical devices, drug delivery systems, nonwoven fabrics, packaging for medical devices, solutions, and drugs, and other applications. It is used in disposable and prefilled syringes, sample cups, diagnostic cuvettes, centrifuge tubes, parenteral kit parts, needle shields, connectors, surgical trays, infectious waste containers and bags, drapes, clamps, spine support boards, and blow-molded containers. Other uses include contact lens molding cups, needle disposal containers, phlebotomy needle holders, infant feeding tubes, medication spoons, analytical test strips, and blood oxygenator membranes. Syndiotactic polypropylene is frequently preferred for applications such as blood bags and sterile garments. It is more transparent than isotactic polypropylene and is more resistant to gamma sterilization. [693, 917, 869, 926]

Tamper-resistant/evident closures can be inexpensively injection molded from polypropylene, and waste containers and bags extruded from polypropylene can be sterilized. Clamps, connectors, and closures for solution bottles can be made by injection molding using the “living hinge” property of polypropylene. Living hinges can be flexed over a million times before failure. (See *Living hinges* (Chapter 2: Morphology) for a description of living hinges in polypropylene). [693, 917, 869]

Polypropylene is also used in health-care related applications such as packaging for health and beauty aids, cosmetics, and nutritional products. It is estimated that over 150 million pounds of polypropylene is used per year in medical devices, with the largest fraction (over 70 million pounds per year) used for disposable hypodermic syringes and other small parts. Polypropylene thermoplastic elastomers and thermoplastic vulcanizates are gaining in popularity for medical applications as replacements for rubber and urethane in applications such as wound dressings, drainage bags, and gloves. Cost

reduction, in addition to allergic reactions to latex proteins and biocompatibility concerns about the use of natural rubber, has led to increased use of these materials. [693, 917, 869, 809, 925]

Useful properties for medical applications include an excellent resistance to solvents and autoclave heat, good tensile strength and stiffness, a long flex life, a high heat distortion temperature, and a low density and moisture vapor transmission rate (MVTR). Polypropylene is easily processed into complex shapes and is generally nontoxic, chemically inert, and tolerant to sterilization. The low to moderate level of additives used for stabilization do not usually interfere with medical use. Polypropylene waste forms noncorrosive incineration products, and the material is easier to recycle than many other polymers. Most polypropylene grades easily pass USP Class VI and Tripartite testing protocols. [99, 917, 693]

The use of polypropylene in medical products is cost-effective. Chemical inertness results in a longer shelf life, and handling costs and costs per unit volume are reduced due to polypropylene's light weight. The cost-effectiveness of polypropylene has led to its substitution for other materials such as glass and other plastics, a trend that is expected to continue with the current emphasis on cost containment in health care. [869, 917, 925]

Several medical applications of polypropylene are shown in Figure 11.10.

11.3 Appliances

Appliance applications of polypropylene include ductwork for dryers; door liners for dishwashers; wash racks and lids for clothes washers; hand mixers; and hair dryers. Mineral-filled polypropylene is used in refrigerator liners, replacing acrylonitrile-butadiene-styrene (ABS). [697]

11.3.1 Small appliances

The use of polypropylene in small appliances is growing, as producers strive to lower production costs; the use of polypropylene is growing faster than any other resin. In kitchen appliances, polypropylene is being substituted for engineering plastics such as ABS, polycarbonate, and polyamide. Although ABS, an amorphous polymer, provides better scratch resistance and a higher surface finish than homopolymer polypropylene (65–80% Gardner gloss scale compared to 95% for ABS), resins like ABS or nylon are 13–20% more dense, result-

ing in increased resin cost. In Japan, filled grades are substituted for ABS in rice cookers and are also being used in coffee makers and large thermos flasks. Processors use barium sulfate fillers to obtain surface finishes similar to those obtained with ABS. Other useful properties for small appliances include abrasion resistance and resistance to fruit

juices, bleach, and cleaning liquids; in addition, high-flow grades allow easier coloring and processing of unique shapes than metal. [793, 791]

Glass-reinforced polypropylene is used in the base of the Bosch-Siemens hand mixer. High rigidity, toughness, and heat resistance enables the resin to withstand severe loads encountered in uses such

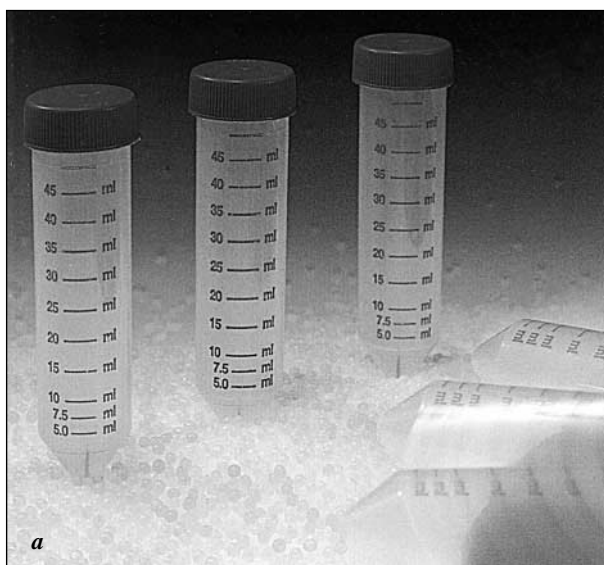
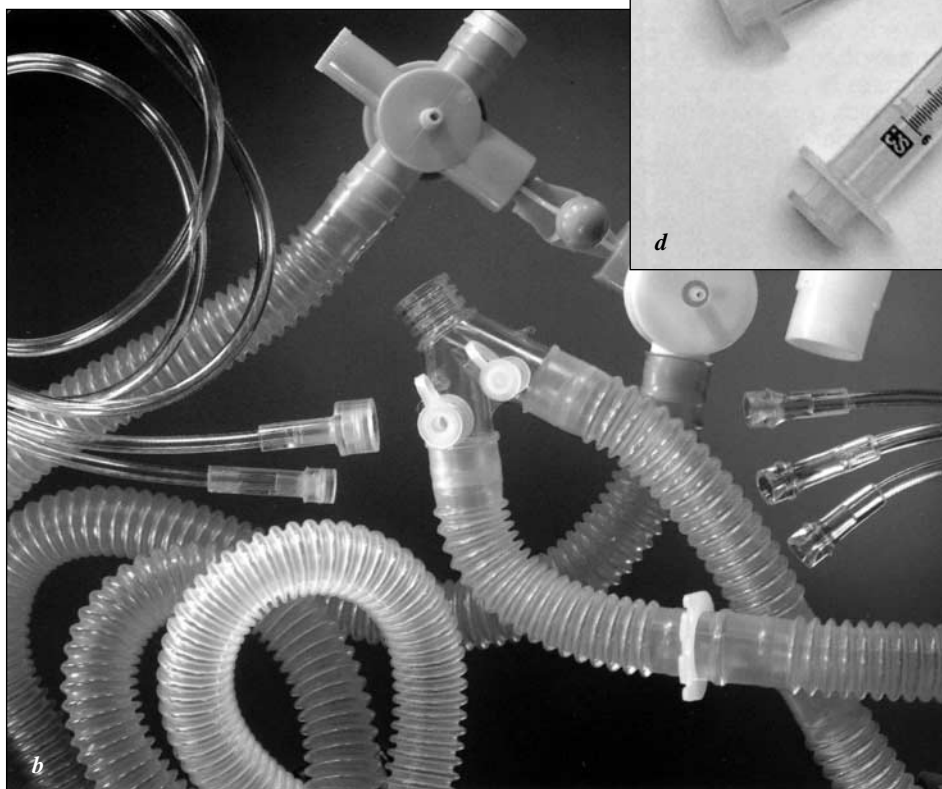


Figure 11.10 Various medical applications of polypropylene. a) centrifuge tubes b) connectors c) syringes and drug containers d) trays, syringes, connectors, woven fabrics e) containers and IV supplies [99, 917, 718, 809, 750]



as kneading dough. The use of polypropylene resulted in lower material costs compared to polyamide, the original material used in the mixer. [706]

The excellent stress cracking resistance of polypropylene makes it useful in commercial hair dryers, which undergo many heating and cooling cycles per day. Polypropylene in the Wella M36 Sensortronic drying hood provides dimensional stability and accuracy, even at high temperatures, and allows snapfit hooks and cable cleats to be integrally molded into the chassis, eliminating additional assembly operations. The resin used (Hoechst Hostacom) is flame retardant, with a UL-94 V-0 rating. [706]

Polypropylene is used in various models of the Rowenta steam irons. In the Dolphino, natural color, stabilized polypropylene replaced polycarbonate. Although changing materials usually requires changing molds, no major mold changes were necessary — only adjustments which took two days to complete. The tank was molded with in-line coloring using a 2% masterbatch. In the Surfline DE41, the upper and lower housing parts and the tank base are made from 10% mineral-reinforced polypropylene; advantages include light weight, heat resistance, and a balanced rigidity/toughness ratio. The surface finish is not affected by long-term exposure to steam, and snapfits can be molded in, allowing for lower cost assembly and easier servicing. [793, 706]

The Rowenta deep fat fryer uses a high gloss, temperature- and scratch-resistant grade of polypropylene. Improved processing and a reduction in the number of different plastics used in the part resulted in high cost savings. [895]

In the juice centrifuge of the multifunctional MK3 kitchen appliance from Bosch-Siemens Hausgeräte, 10% mineral-reinforced polypropylene withstands very high mechanical stress due to the high-speed centrifuge (2400 rpm). The easy-flowing, hard and rigid grade can withstand the centrifugal force over the long-term and can be injection molded in a filigree part with 2304 openings (Figure 11.11). [654]

The pump housing and the flange between the motor and housing in the BADU “90” swimming pool pump is made from 30% glass-reinforced polypropylene. Material damage due to heat from the pump is eliminated because of the high heat deflection temperature (HDT/B of 155°C; 311°F); other useful properties are chemical resistance, ri-

gidity, toughness, and dimensional stability. The pump is thick-walled but lightweight, due to the low density of polypropylene. [706]

Several applications of polypropylene in small appliances are shown in Figure 11.11.

11.3.2 Large appliances

Use of polypropylene in large appliances is increasing, due to its low cost and the enhanced properties of newer grades. Polypropylene is competing with thermosets, metals, and other thermoplastics such as styrenics. The weight of polypropylene used in washing machines was estimated as 22 lb./unit in 1995; use is expected to rise to 44 lb./unit in 2000 as it replaces engineering polymers. [791]

Polypropylene is used in washing machine drums (typically 30% glass-reinforced, 40% talc-filled, and homopolymer). Unfilled polypropylene is used in drums for top-loading machines at spin speeds of ~600 rpm; a glass-reinforced grade is now used in a front-loading drum with a spin speed of 1200 rpm, replacing metal. In 1995, General Electric began using an injection molded glass-reinforced polypropylene drum to eliminate the need for metal stamping. Other applications include pump housings; 90% of all West European washing machines have plastic pump housings, with a 60:40 ratio between talc-filled and glass-reinforced grades. Talc-filled bases are used for washing machines, washer-dryers, and dishwashers, primarily for cost reduction; however, the use of polypropylene also eliminates corrosion and allows structures and supports to be built in for functional integration. [791, 895]

Substitution of polypropylene for established resins such as ABS requires changes in processing, including minimizing the length of the parting line due to the higher flow rate of polypropylene compared to ABS, and the necessity of designing reinforcements such as ribs into housings to compensate for the lower structural strength. Newer grades designed for large appliances have increased stiffness, higher temperature and deformation resistance, and improved surface hardness, and they are easier to process. The sound-deadening properties of polypropylene compared to metal are useful when appliances in smaller dwellings are placed in the kitchen instead of the basement or laundry room, and the recyclability of polypropylene aids in meeting consumer demands for recyclable components and in adhering to environmental regulations. [791]

Whirlpool uses polypropylene reinforced with 30% chemically coupled glass fibers for a washing machine drum; spin speed of the machine is 1200 rpm. The geometry of the drum was optimized using

a CAD study that simulated the deformation of the washing machine drum at high spin speeds, in order to offset high-speed stresses. To improve the connection between the motor and the container, belt pre-

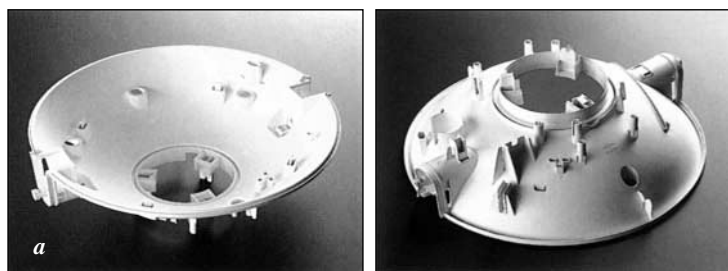
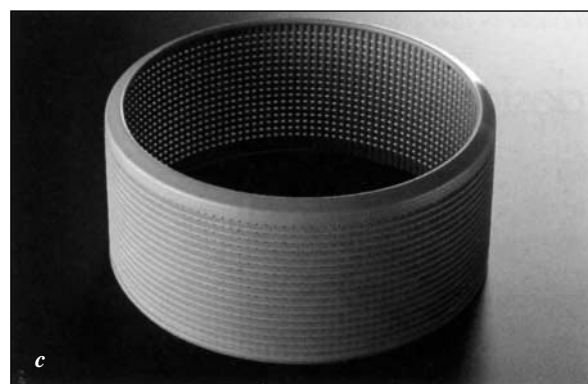
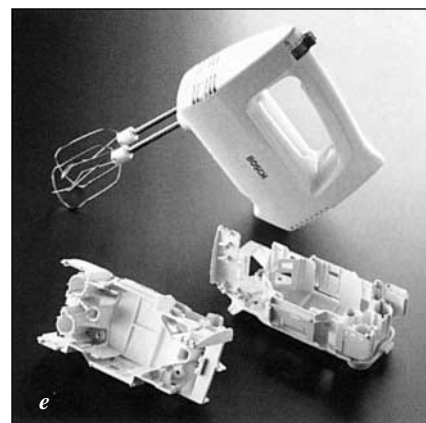
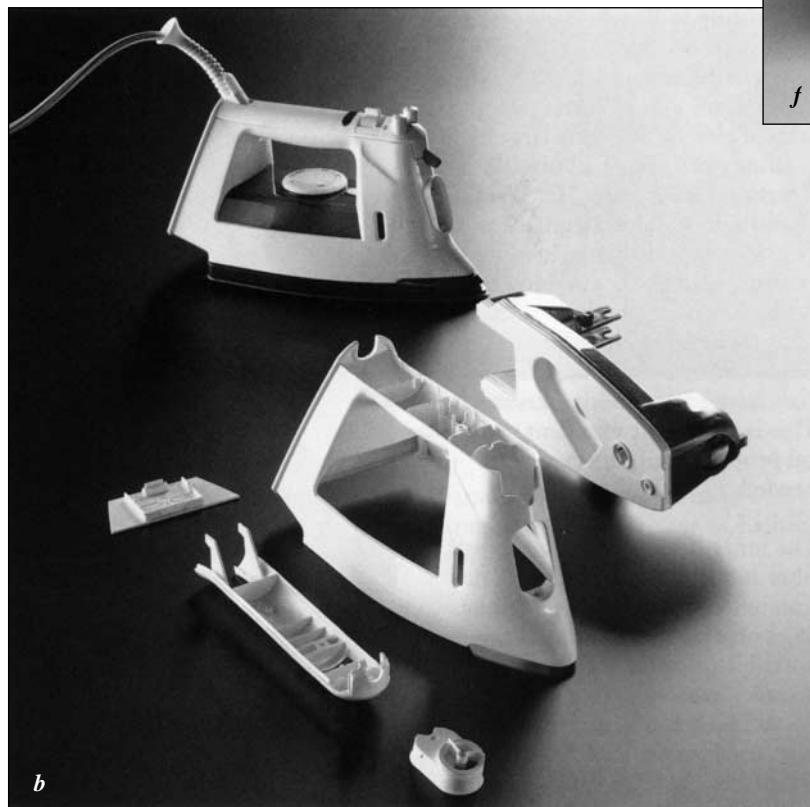
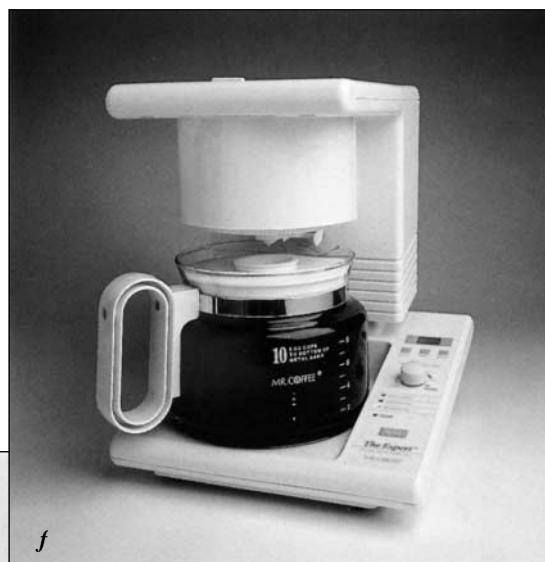


Figure 11.11 Applications of polypropylene in small appliances (a -e made of Hostacom from Hoechst; f from Amoco) a) parts for a commercial hair dryer b) steam iron; body is made from polypropylene c) juice centrifuge d) swimming pool pump e) hand mixer f) coffee maker [706, 654, 718]



tensioning was used to compensate for material creep. Use of polypropylene led to a lower cost production process, better integration of functions, and a water- and energy-saving part design. [654]

A 40% mineral-reinforced grade is used in the dispenser dish of a Miele washing machine. The most important requirement of a dispenser dish is detergent resistance; a second requirement is the



Figure 11.12 Polypropylene applications in large appliances. a) The inner door of a washing machine b) A washing machine drum c) The dispenser unit for a washing machine d) A washing machine pump e) Dispenser unit for dishwashers. All are made from Hostacom from Hoechst. [654]

ability to withstand a reasonable amount of stress due to vibrations of the motor. The rigidity of polypropylene and its excellent chemical resistance make it useful for this application, and the dish design, with three compartments, allows for water penetration throughout the dish and for efficient detergent removal. [654]

Polypropylene (30% mineral-reinforced) is used in the inner door of a Bosch-Siemens-Hausgeräte GmbH tumbler dryer that has the largest loading porthole of all tumble dryers on the market. The inner door with integral fluff filter holder ensures perfect closure of the porthole opening and serves as a carrier for the outer door. The good rigidity, high dimensional accuracy, and high heat deflection temperature (HDT/B of $>120^{\circ}\text{C}$; $>240^{\circ}\text{F}$) of polypropylene ensure tight door closure and reliable dryer operation. High gloss provides a pleasant appearance, and very good flow properties are useful for large parts. [706]

Several applications of polypropylene in large appliances are shown in Figure 11.12.

11.4 Textiles and nonwovens

Polypropylene fibers are used in carpeting, automobile interiors, apparel, geotextiles, and nonwoven applications. Polypropylene is versatile, colorfast, chemically resistant, economical, lightweight, and environmentally friendly. It has good insulating properties and a soft textile feel, and fibers are insensitive to moisture and dirt. Use of polypropylene in textiles has grown since the mid-seventies; textile applications now account for 25% of the total polypropylene market in western Europe, comprising 20% of western Europe's synthetic fiber production. Additional properties and applications of specific types of fibers can be found in Chapter 7: Fibers. [719, 705]

11.4.1 Floor coverings and home furnishings

Polypropylene floor coverings are used in homes, offices, and automobiles. Polypropylene fibers are also used in upholstery fabric, wall coverings, and bedding. Polypropylene is economical — its low density provides more fiber per pound of polymer — and durable, able to withstand years of traffic with no change in appearance. Due to its low weight compared to other fibers, carpets can be produced with more volume but with the same surface weight. Floor coverings are stain resistant, colorfast, static resistant, and nonallergenic — poly-

propylene is not affected by moisture, mold or mildew and doesn't support fungi or bacteria. [719]

11.4.2 Automotive

Needlepunched polypropylene carpeting has been developed for automotive use. It is lightfast and aging resistant and is used in floorcoverings, rear parcel shelves, and in the boot. The use of polypropylene in automotive textiles, in addition to the diversity of other automotive applications of polypropylene, aids in the goal of achieving a single-material system for easy recycling. [705]

11.4.3 Apparel

The wicking action of polypropylene makes it useful in clothing for outdoor sports, such as hiking, skiing, biking, and swimming. Polypropylene does not absorb moisture, so polypropylene clothing worn next to the skin does not get wet from perspiration; the moisture passes through the material into the air or to an outer absorbent material, such as cotton. Clothing also dries faster. The low density of polypropylene makes it lightweight (the only fiber lighter than water), useful in swimwear, biking shorts, and other apparel. Gases, such as oxygen, pass through the material; this "breathability" ensures that the wearer remains cool and comfortable, even in warm weather. [719]

Polypropylene apparel resists fading, odors, stains, mold, mildew, and bacteria. It is easy to care for; it is colorfast, even in chlorinated environments, and light and dark colors can be washed together. Most apparel can be dried in home dryers at low temperatures. [719]

11.4.4 Industrial applications and geotextiles

Polypropylene is used in filters and filaments, as cordage for rope, fish netting, and other applications. Cordage is lighter than water, so nautical ropes float, and the strength-to-weight ratio is up to ten times that of steel. The nonwetable fibers are useful in oil-absorbing booms, soaking up oil, fuel, hazardous wastes, inks, and solvents. Other uses are in woven packing bags (Big Bags), strapping tape, binder twine, tarpaulins, artificial grass, tow ropes for motor vehicles, and brushes. [705, 773, 719]

Filtration products are used in the medical, electronics, chemical, mining, and food processing industries. They are used in biotechnology and medical research for cell separation, tissue cultures, fluids filtration, water purification, drug preparation, and blood treatment. Filters are used

in clothes dryers, power tools, coffee machines, and water filters. The woven mesh structure filters out water, oil, fuel, lint, debris, food, and other impurities. Filters are available that meet FDA re-

quirements for food contact applications (CFR Title 21) and can be obtained in a variety of forms — bags, tubes, pouches. [869, 719]

Geotextiles can be woven or nonwoven. They are

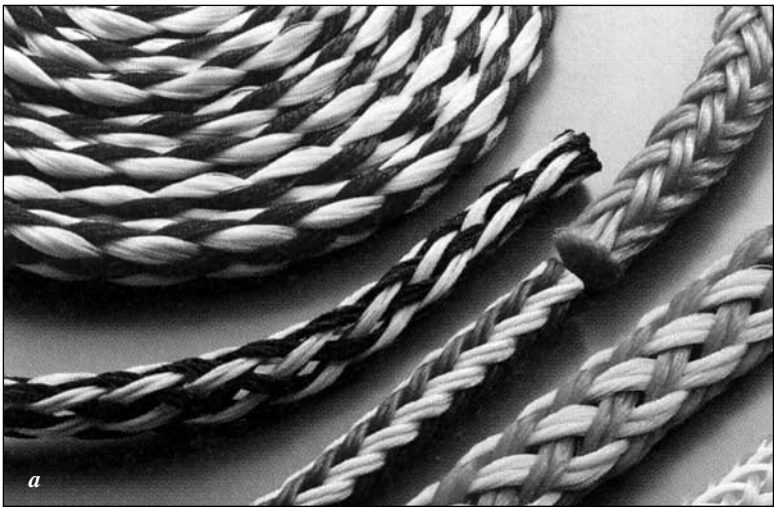
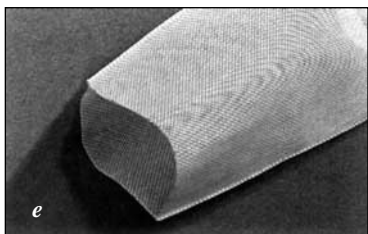
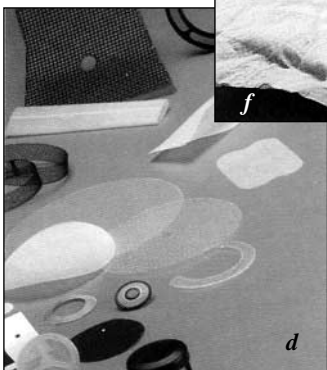
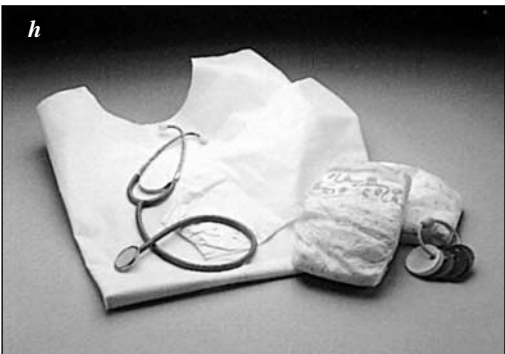


Figure 11.13 Polypropylene applications in textiles and nonwoven fabrics. a) rope b) outdoor apparel c) geotextiles d) and e) woven filters f) disposable diapers g) packing bags (Big Bag) h) surgical garments i) automotive upholstery and automotive interior cladding part with trim [705, 719, 869, 718]



used in building and construction sites and in landfills. In concrete and asphalt paving installations, geotextiles reduce crack formation and increase pavement strength and durability. At construction and landscaping sites, they stabilize soil against erosion, prevent sediment run-off, and promote rapid revegetation. Open-mesh fences reduce wind, sand, and snow damage, provide crowd control at concerts and sporting events, and protect hazardous work sites and utility areas. All geotextiles have high tear strength; other properties can be tailored to the particular application by the choice of grade and processing parameters. [705, 719]

11.4.5 Non-wovens

Nonwoven fabrics are used in sanitary products, surgical garments, geotextiles, and other applications. In sanitary products — disposable diapers, feminine hygiene products, and adult incontinence aids — a soft non-woven cover stock maintains dryness and comfort. Fibers have high tear strength, even when wet, and moisture is transported through the material. Disposable surgical non-wovens, including shoe covers, gowns, caps, and bedding, are economical and ensure proper sanitation. Non-woven bouffant caps, wipes, and cleaning pads are used in restaurants and food service areas to keep food preparation areas free of contamination. Other uses include carpet backing, mattress pads, cushions, vacuum cleaner bags, overnight courier envelopes, and automotive car covers.

Protective garments prevent contamination of sensitive appliances in ultra-clean rooms by workers. Agricultural non-wovens provide air, light, and water permeability to seeds and plants and protect against cold, bad weather, and insect pests. As a result, early sowing is possible, and plants grow well, with a high yield. [705, 719, 654]

Several applications of textiles and non-woven fabrics are shown in Figure 11.13.

11.5 Packaging

Packaging is used to contain, protect, and identify the products within the package. Packaging protects the product from mechanical damage and biological attack and informs the customer about such topics as the product's size, ingredients, and instructions for use. It provides convenience throughout the life of the product — during shipping, retail, and final use — and can help preserve freshness of food products that are likely to spoil.

The most important application for plastic packaging is in food packaging. [893, 891, 895, 890]

11.5.1 Plastics vs. other packaging materials

Common packaging materials include wood, glass, metal, paper, and plastic. Advantages of plastics as packaging materials include easy processing, low cost, and lower weight due to a lower density than other packaging materials. Plastic packages can be optimized for a particular application, and they are more impact resistant than glass, which breaks when dropped and requires more careful handling. Plastics have a lower volume occupancy than glass; for the same strength as plastic, glass packaging requires a higher volume and weight. For example, a plastic drink bottle with a wall thickness of <1 mm (0.04 in.) is equivalent in strength to a glass bottle with a wall thickness of 2–3 mm (0.08–0.1 in.). [893]

Disadvantages of plastics include environmental stress cracking, poor stacking strength compared to other packaging materials, and problems with sterilization when used in medical applications. Due to a similar molecular structure, polyolefins such as polypropylene can absorb paraffins and solvents, which can cause deformation. Unlike glass and metals, plastics do not provide a complete barrier to gases and moisture. However, new techniques such as lamination or coextrusion, or a combination of plastics with other packaging materials (paper, aluminum foil) can provide good product protection. [893]

11.5.2 Use of polypropylene in packaging

One-third of all polypropylene applications is in packaging. Polypropylene is used in packaging biscuits, crisps, sweets, bread, pasta, dairy products, convenience foods, dried fruits, snacks, syringes, and medicine bottles. Polypropylene films are used in flexible packaging, for shirts, hosiery, bread, and produce, and in shrink-wrap applications for toys, games, hardware, frozen foods, and cigarette wrap. Use of polypropylene in packaging is growing, especially in blow molded containers, sheet, profile and film extrusion, and injection molded packaging. New grades with high stiffness, high clarity, and good elastomeric properties have enabled polypropylene to replace both plastic and non-plastic packaging materials. The trend in packaging toward thinner walls, lighter weight, and greater stiffness (in order to conserve resources) fits well with polypropylene's balanced combination of properties:

toughness, stiffness, hardness, excellent chemical resistance, and low density. [895, 797]

Some estimates indicate that up to two-thirds of polypropylene's growth is due to replacement of other thermoplastics. Polypropylene has replaced the more expensive polystyrene in many food packaging applications due to a lower cost and properties such as toughness, resistance to stress cracking, and favorable organoleptic properties. It is being considered as a substitute for PETP in applications such as dairy containers and peanut butter jars due to the increased clarity of new resins, and oriented, coextruded films are used as a replacement for cellophane in the snack food industry. [895, 890]

Polypropylene is preferred over polyethylene terephthalate (PET) for use in hot-filled products such as juice drinks due to its resistance to high temperatures (heat distortion temperature at 66 psi of 99–127°C (210–260°F) compared to 38–129°C (100–264°F) for PET). Although its oxygen barrier properties are poor, polypropylene provides five times the moisture vapor transmission (MVT) performance of PET and at least ten times the MVT of polystyrene, making it useful in packaging dry foods and moisture-sensitive products such as coated analgesics and vitamins. The use of polypropylene packaging in these applications extends shelf life and can eliminate the necessity of adding dessicants to the container to prevent moisture accumulation. [927]

11.5.3 High crystallinity and high melt strength grades

High melt strength grades of polypropylene allow it to be processed on high-speed, wide-web (up to 142 cm; 56 in. wide sheet) packaging equipment commonly used in the food industry. Conventional low-melt strength polypropylene cannot be processed on wide-web equipment due to a tendency to sag during sheet extrusion. Low melt strength also causes a rapid wall thinning, so that thicker walls are necessary to account for nonuniform wall thicknesses. Heterophasic copolymers, such as polypropylene polymerized with ethylene-propylene rubber, are also used on wide-web equipment and are commonly used in such melt-phase thermoformed products as microwaveable food packaging due to low odor and taste transmission properties. [894, 797]

Highly crystalline grades (HCPP) are used in producing highly rigid film (film for labels), very thin-walled flexible packaging (twist film, stand bags), and thermoformed articles. They are used in

disposable packaging for microwave foods due to improved heat resistance and low creep. [895]

11.5.4 Clarified polypropylene

Polypropylene random copolymers have moderate clarity, although the clarity of polyolefins is generally sensitive to processing conditions. The addition of clarifying agents to random copolymers provides see-through clarity to polypropylene packaging, important in many packaging applications such as rigid containers. Combined with the other favorable properties of polypropylene (heat distortion temperature, stiffness, impact strength, cost, recyclability, etc.), clarified resins compare favorably to other materials used in rigid packaging, such as PET, styrene-acrylonitrile (SAN), polystyrene, and polyvinyl chloride. Clarified polypropylene is clearer than HDPE and has superior organoleptic properties and heat resistance — it can be hot-filled at temperatures up to 100°C (212°F) compared to 91°C (196°F) for HDPE. [890, 927]

Clarified polypropylene sheet is used in thermoformed cups for Brisa purified water as a replacement for the more costly polystyrene. The eight-ounce foil-sealed cups are equal in clarity to polystyrene and provide an eight-week shelf life, compared to 3–4 weeks for polystyrene. The polypropylene cups are resistant to ozone and have better organoleptic properties. They are more rigid and tough than polystyrene cups, with better organoleptic properties, and are ozone-resistant. They can be easily crushed after use without breaking into a number of shards. [927]

11.5.5 Metallocene polypropylene

The development of metallocene catalysts has resulted in improved properties for packaging applications, including greater puncture resistance, higher impact strength, greater low temperature impact strength, and better organoleptic and optical properties than Ziegler-Natta polypropylene. Metallocene resins for packaging applications also have good flow resistance, high stiffness, high transparency, and high heat resistance. High gas permeation rates of metallocene resins make them useful in packaging vegetables, which continue to respire after packing. [895, 893]

The enhanced clarity of metallocene polypropylene (mPP) makes it useful in thinwall, transparent molded packaging such as frozen food packaging. Transparency of one grade of mPP homopolymer (M Novolen NX 50081; BASF AG) in supplier trial runs

was 93%, compared to 47% for high-crystallinity polypropylene and 89% for new clarified, nucleated resins. Random copolymer mPP was even more transparent (95% transparency) and was only slightly lower than that of polyethylene terephthalate (PET; 100% transparency). Trials of metallocene polypropylenes with melt flow rates from 4 to 120 indicate that nucleators, used to increase the crystallinity, stiffness, and clarity of conventional polypropylene, also benefit mPP. [929]

The high melt flow rate of mPP reduces cycle times when molding thin-wall containers while still providing toughness and stiffness. Cycle time of a 60 MFR mPP was 10% faster than a nucleated grade, with comparable clarity and gloss. Cycle times of 60 MFR mPP and a high crystallinity grade were equal, but the mPP provided significantly higher clarity and gloss. [929]

New free-flowing mPP grades for injection molding are suitable in applications such as tubs for dairy products, ice cream, and cosmetics containers and for thin-walled non-food packaging and high-volume transport containers and crates. [895, 893]

11.5.6 Rigid packaging

Polypropylene is widely used for rigid packaging, such as margarine tubs, yogurt containers, trays, milk jugs, and bottles. Thermoformed polypropylene margarine tubs have replaced most PS and PVC tubs. Random copolymers are frequently used in products such as food storage containers due to their excellent clarity and good balance of impact strength and stiffness. In thinwall parts, such as injection molded delicatessen containers or yogurt cups with a length-to-thickness ratio of up to 400:1, use of polypropylene copolymers with high melt flow rates (35 g/10 min) can reduce container weights by 30% over containers produced with other materials. Containers are tough, rigid, and recyclable. They provide a moisture barrier and top-load strength, and the low-temperature resistance protects the product at refrigerator temperatures. [928, 890, 691, 927, 654, 895]

Polyethylene is the material most used in rigid packaging; however, due to its lower flexural modulus compared to polypropylene, it requires a greater wall thickness in thin-walled containers. Polypropylene is used in screw-on caps and closures, due to the resin's stiffness, resistance to stress cracking, and living hinge properties, and it is used in tamper-evident closures for medicines, liquor, and food products. Polypropylene is re-

placing HDPE in applications such as crates and paint containers. [928, 890, 691, 927, 654, 895]

Biaxially oriented, clear polypropylene bottles and jars produced by a single-stage injection blow molding process may compete with PET containers as a substitute for glass containers. Oriented polypropylene is one-third less expensive than PET, even when allowing for extra wall thicknesses to compensate for higher flexibility. It performs better in hot fill applications and has good water barrier properties; however, polypropylene is a poor barrier to gases, and methods to coat the material with a better barrier polymer such as polyvinylidene chloride or EVOH are currently under development. Possible applications for these containers include pasteurized products, pickles, sauces, creams, instant coffee, and powdered milk. [930]

Polypropylene is suitable for containers used in microwave cooking, as long as the food product does not have a high fat content and the container is designated as "microwave use only". In these cases, the moisture in the food ensures that the food temperature does not exceed 100°C (212°F), which is near the hot fill temperature limit of polypropylene. Blends of materials are used in containers designed for dual oven use. For example, a blend of polypropylene, molded pulp, fillers and additives can withstand temperatures from -40°C (-40°F) to 200°C (392°F), similar to CPET. The containers have a pearlescent finish and lack the wrinkled corners common on paperboard trays. Many microwaveable products contain several layers of different materials for shelf-stable packaging (see *Barrier packaging*). Shelf-stable products may be stored at ambient temperatures and do not require refrigeration. [890, 930]

Examples of polypropylene in rigid packaging include a coffee cream jug (Figure 11.14) made of a single material for easy recycling. The design incorporates a tear-off ring that can be pulled with the lid strip. The high impact strength and low-temperature resistance of polypropylene provides product protection during transport, on the supermarket shelf, and in the refrigerator. A high-clarity polypropylene is used as the container for Pledge Household Cleaner (Figure 11.14), due to its combination of clarity, impact strength, and economy. The bottle, with a linerless polypropylene closure, is produced using a single material for easier recycling. [654, 894]

Recent environmental regulations concerning the use of packaging material has led to increased

use of polypropylene in rigid packaging. To reduce the amount of packaging that ends up in landfills, many US states require that packaging materials be reduced in weight, have 25% post-consumer recycled content, or be recycled at a particular rate. Polypropylene is more easily recycled than other resins and can be recycled in small amounts (~10%) as a component of the high density polyethylene (HDPE) waste stream. Also, its low density reduces the weight of the package. [928,927]

11.5.7 Film

Polypropylene is used in flexible packaging in applications such as shrink-wrap films, snack food packaging, textile bags, and cigarette packaging. Oriented polypropylene is the second most dominant material used in packaging, surpassed only by polyethylene, and the use of polypropylene in films is increasing.

Although three types of materials are used in flexible packaging — paper, thin gauge aluminum, and plastics — plastic films are more in demand than both of the other materials combined. [794]

Biaxially oriented polypropylene (BOPP) film is used in packaging for biscuits, crisps, baked goods, sweets, bread, pasta; in cigarette wrap, shrink wrap, and shrink labels; in lamination of books and magazines; in office stationery films; in industrial laminates and supports for adhesive tapes; and in films for metallization used in applications such as gift wrapping and snack food packaging. It is commonly used for packaging products that must be protected against moisture absorption or loss. Coextruded OPP films are used in the snack food industry as a replacement for cellophane. [729, 890]

Opaque, coextruded, oriented polypropylene film (pearlized or cavitated) is formed from coex-

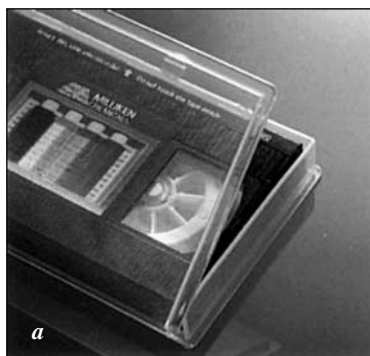


Figure 11.14 Applications of polypropylene in rigid packaging. a) a VCR case with a living hinge b) drug packaging c) blow-molded container for household cleaner (Pro-fax; Himont) d) container for purified water, similar in clarity to PET e) candy containers f) dairy containers (Amoco) g) packaging for compact discs h) clear color packaging for household products i) Brisa single-serve bottled water containers j) a coffee cream jug, made of a single material for easy recycling (Hostalen; Hoechst) k) ketchup bottles [927, 762, 718, 654]



trusion of three layers; the outer layers are homopolymers or copolymers, and the middle layer is a homopolymer containing small particles. The particles are usually calcium carbonate, although polyamides or polyesters are also used. Copolymers are preferred for the outer layers due to good cold seal adhesion, good heat sealability, and ease of conversion. During the orientation process, voids are formed within the core layer, which lowers the density to 0.62–0.72 g/cc (from 0.91 g/cc for uncavitated OPP). The voids also cause light to be scattered, resulting in an opaque film useful for packaging fat-containing products such as chocolate and high-fat biscuits. With cavitated film, the high fat foods do not create the appearance of an oily deposit on the outside of the product when they come in contact with the packaging. [890]

Polypropylene film provides excellent ultraviolet resistance and transparency, and additives can be used to increase performance properties. It can be printed, laminated, and metallized and is easy to handle on automatic packaging machines. Several applications of polypropylene packaging are shown in Figure 11.15. [890]

11.5.8 Barrier packaging

Different materials vary in their ability to limit passage of gases, liquids, and solids. Metals and glass (without any pinholes) are impermeable to everything, while paper is permeable to almost everything. Due to their nonpolar molecular structure, polyolefins have a very low water permeability but are readily permeable to gases such as oxygen and carbon dioxide and to hydrocarbons. [893]

Barrier materials are coatings or multilayer combinations of plastics designed to reduce water and gas diffusion into and/or out of the rigid or flexible package. Barriers to oxygen are necessary to preserve food freshness; oxygen can cause a chemical change in the product and rancidity in fat products. Water vapor can change the physical appearance of a product by either caking a dry material (i.e. flour) or by causing it to become soggy. Carbon dioxide does not cause food spoilage and is used to protect some foods against spoilage. Barriers to other gases such as nitrogen are used in modified atmosphere packaging to extend the shelf life of fresh foods without the use of preservatives. The use of barrier packaging methods has reduced



food spoilage to 2–3%, compared to 30–50% in Third World countries where packaging techniques are less developed. [890, 930, 893]

Polyvinylidene chloride, polyamide, and ethylene vinyl alcohol (EVOH) are commonly used as barrier polymers in coatings and coextrusions. A typical multilayer structure consists of two layers of polypropylene separated by a layer of ethylene vinyl alcohol, with adhesive layers (tie layers) to hold the polypropylene and EVOH layers together. The plastic ketchup bottle is composed of this multilayer

structure, with polypropylene for rigidity and water vapor resistance and EVOH for oxygen resistance. “Lamipac” trays, made of a six-layer structure based on polypropylene/polyvinyl chloride/polypropylene, are used in General Foods’ “Today’s Choice” ready-meals and “Sheba” cat food. The “Lamipac” containers are closed by a vacuum heat seal process and are shelf stable (shelf-life of up to 24 months), retortable, and microwaveable. “Top Shelf” entrees from Hormel are vacuum packed in a four-layer polypropylene tray using polyvinyl chlo-

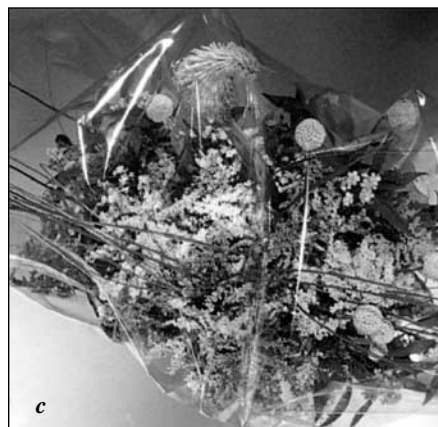


Figure 11.15 Applications of polypropylene films in packaging. a) snack food packaging using metallized film (Amoco) b) snack food packaging using clear film (Amoco) c) floral packaging (Escorene; Exxon) d) apparel packaging (Escorene; Exxon) [718, 729]

ride as the barrier layer; product shelf-life is up to 18 months. The easy-open lid is also a multilayer structure. [890, 928, 930]

Modified atmosphere packaging (MAP) is used for fresh products such as meat, fish, pasta, poultry, salads, and vegetables, in order to satisfy an increasing demand for fresh, additive- and preservative-free foods. In these packages, the composition of the natural air atmosphere inside the

container is replaced by a gaseous mixture. The gases used depend on the product but generally include nitrogen (an inert gas used to replace oxygen) and carbon dioxide (to retard the growth of mold and aerobic bacteria). High barrier materials, such as a laminate of PVC rigid foil and polyethylene film, are generally used for the container; however, laminated materials such as polyvinyl chloride-coated oriented polypropylene are used in

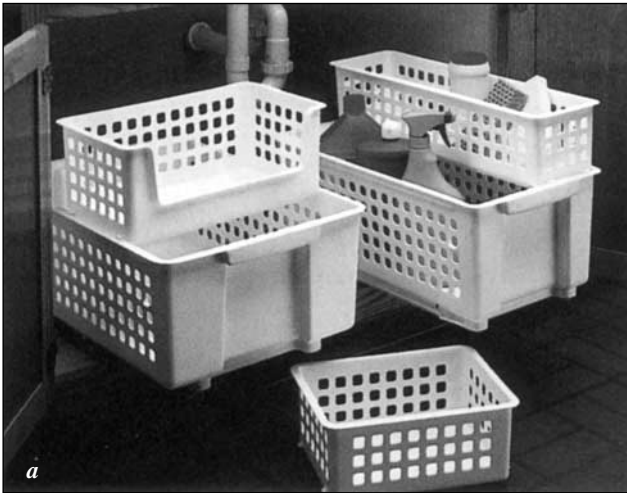
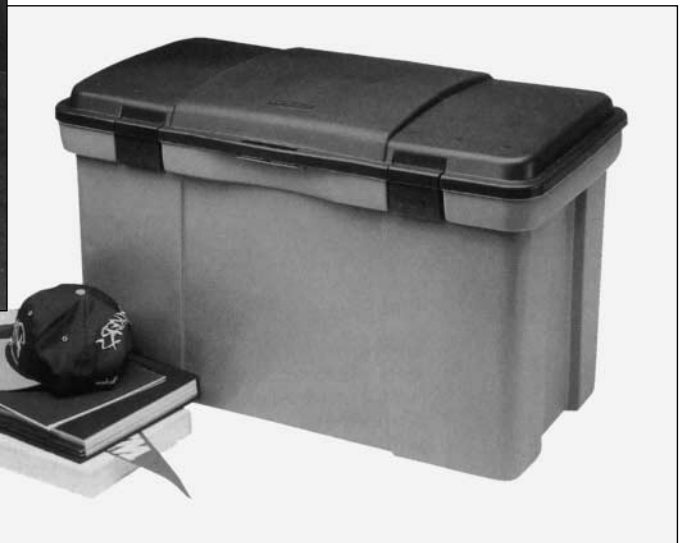


Figure 11.16 Polypropylene applications in housewares. a) stackable laundry baskets (Rubbermaid) b) 33-gallon ToteLocker (Rubbermaid) c) clear food containers d) various household products [792, 718]



the lids of thermoformed MAP trays. [930, 890]

11.6 Consumer products

Polypropylene is used in other applications such as housewares, recreational equipment, toys, office equipment, and lawn furniture. In housewares, polypropylene is used in large and small containers for food and other uses (Figure 11.16). Random block copolymers, which combine a random copolymer matrix with a dispersed rubber phase, and improved random copolymers provide high clarity and low-temperature impact strength, important in housewares used in freezer storage. New, high-flow grades of random and impact copolymers allow the molding of oversized, high performance housewares such as the deep, 33-gallon (125 L) ToteLocker and 50-gallon (190 L) RoughTote by Rubbermaid, the under-the-bed and hangable closet clothing bins by Sterlite, and the 10-quart (9 L) “fresh-food keepers by Culver. [792, 691]

Polypropylene’s low density makes it useful in recreational items such as bicycle helmets, ice coolers, surfboards, and flotation devices, and its toughness is useful in luggage and lawnmower parts. Polypropylene is used as a substitute for ABS in “hard”, injection molded luggage, although most “hard” luggage (66%) is still made from ABS. New grades of enhanced polypropylene are being used in lawn furniture, providing higher stiffness and warp resistance and lighter weight than the commonly used 20% and 40%



Figure 11.17 A cordless lawnmower. The mower deck, cowling cover, and discharge chute are made from high impact polypropylene (Ferro Corp.) [931]

talc-filled grades. High impact polypropylene is used in the deck, cowling cover, and discharge chute of a new cordless lawnmower (Figure 11.17). Polypropylene (UV stabilized, 20% calcium-filled) provides durability and safety in the mower deck, and a proprietary grade in the cowling cover and discharge chute provides good long-term weathering resistance and a high-gloss Class A finish. [899, 895, 931]

Wheels on the Ryobi self-propelled, battery operated lawnmower are made from a long glass fiber reinforced, chemically coupled polypropylene composite. The material provides strength, chemical resistance, lubricity, and moisture resistance. High strength is required in the two front drive wheels, where final gear reduction takes place through molded-in gear teeth (Figure 11.18), and the fertilizers and pesticides sprayed on the lawn require that the wheels be resistant to chemical attack. The low moisture absorption of polypropylene provides good dimensional stability for the gear teeth, even when the mower is run in damp grass and stored outside. Also, the natural lubricity of the material allows the gears to run in a dry state, eliminating the need for grease which would collect dirt and cause greater wear. Other materials considered were mineral-filled polypropylene, which lacked the required strength, and polycarbonate, which was not as chemically resistant. [932]

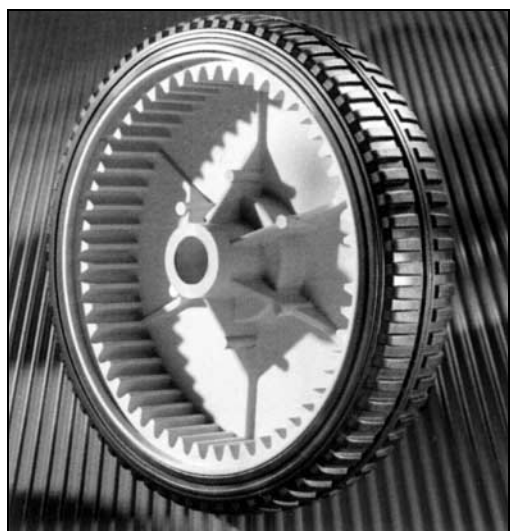


Figure 11.18 Drive wheel on the Ryobi self-propelled, battery-operated lawnmower, made from a long glass reinforced, chemically coupled polypropylene composite (Verton MFX; LNP Engineering Plastics). Gear teeth are molded into the wheel. [745]

11.7 Building and construction

In the building and construction industries, polypropylene is used in walls and partitions, as insulation for power cables and telephone wires, and in pipes. Pipe applications include underfloor heating, hot and cold water, sanitary engineering, and pipe fittings (Figure 11.19). [674, 928, 712, 654]

Polypropylene pipes have a long service life, good impact strength, and good chemical resistance. They are nontoxic, with a neutral taste and odor, and are easily welded. Pipes provide long-term pressure resistance, and heat stabilized pipes can withstand high service temperatures. Pipes do not

corrode and do not attract lime deposits. Polypropylene block copolymer was used as the material for pressurized pipes by Hoffman-LaRoche AG to carry waste water from chemical production to a treatment plant, a distance of 3.6 km (2.2 mi). Two pipelines for alternating operation were laid in an underground tunnel large enough to walk through. The material had to withstand pH values of from 1.5 to 15, an operating pressure of 2.3 bar (33.3 psi), and temperatures up to 35°C (95°F); the block copolymer exhibited better creep strength at higher temperatures than other pipe materials and performed better in heat aging tests. [712, 654, 934]

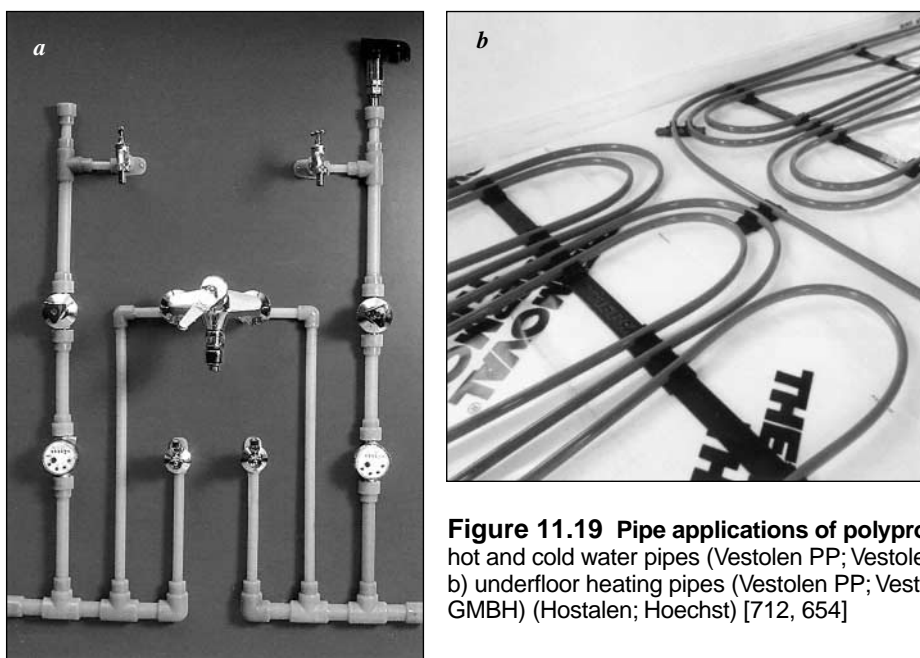


Figure 11.19 Pipe applications of polypropylene. a) hot and cold water pipes (Vestolen PP; Vestolen GMBH) b) underfloor heating pipes (Vestolen PP; Vestolen GMBH) (Hostalen; Hoechst) [712, 654]

12.1 Design fundamentals

12.1.1 Design overview

Polypropylene is one of the most widely used thermoplastics. It ranks third in consumption, close behind low density polyethylene and PVC (Figure 12.1), and with a world-wide growth rate of about 7%, it is likely to overtake PVC soon.

The reason for this popularity lies in the versatility of the material, indeed polypropylene is arguably the single most versatile plastic. It has a good combination of properties, a comparatively low price, and it can be processed by a wide variety of techniques. These benefits derive from the very nature and structure of the material. Polypropylene is produced by polymerizing propylene gas, either alone or in the presence of minor proportions of other monomers. By controlling the monomers, catalysts and process conditions it is possible to produce a wide variety of polypropylenes. These macromolecular fundamentals make it

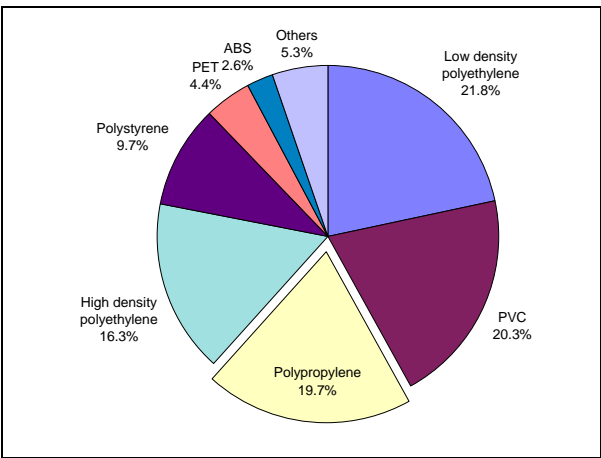


Figure 12.1 Polypropylene share of world 1996 thermoplastics consumption. [1216]

possible to tailor polypropylenes to a wide range of duties and applications, hence the versatility of the material.

The possibilities are further enlarged by the

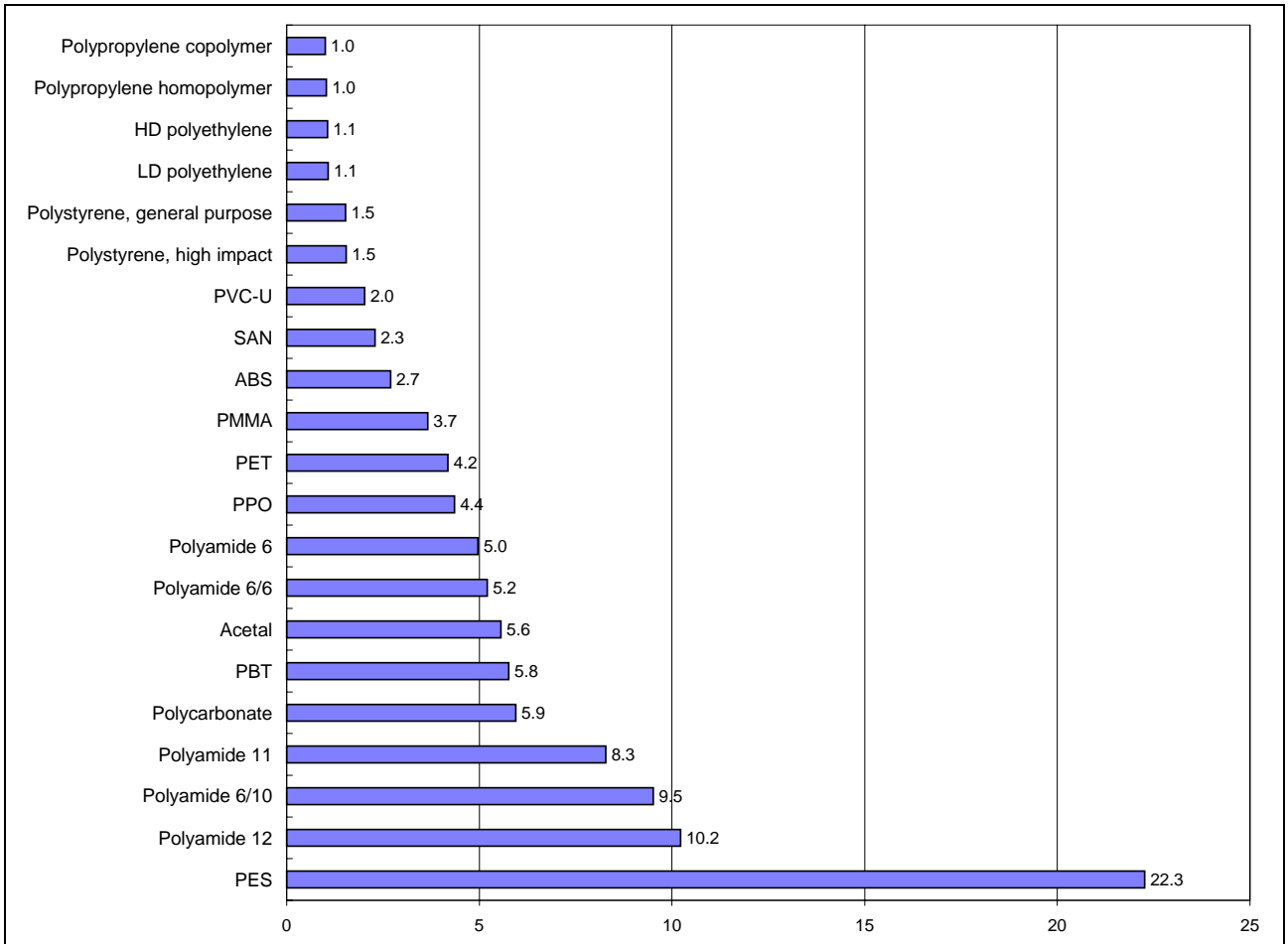


Figure 12.2 Unit volume cost of polypropylene compared with other thermoplastics. [1103]

ability — much superior to that of polyethylene — to accept fillers and reinforcements. These together with clarifiers, nucleating agents, lubricants, release agents, and anti-static agents are used by polymer manufacturers and compounders to produce a vast spectrum of polypropylenes adapted to specific processes and end uses. There are more than 3,000 different commercial grades of polypropylene available to the designer and manufacturer.

Furthermore, these advantages are available at low cost. The commercial success of polypropylene is assured by pricing that makes it the most economical of thermoplastics. The most straightforward way to compare polymer prices is to look at the cost for a unit volume of basic grades, then express the variation between them as a ratio (Figure 12.2). The resulting index should be substantially independent of currency and price changes. Unit volume cost is a truer guide for the designer than weight costs but it is not infallible. Remember that a stronger material can be used in less volume than a weaker material, so a more expensive material may result in a cheaper product.

The volume cost of different polypropylene grades can vary by a factor of three or more, depending on the additives and technology involved (Figure 12.3). Production volumes and niche premium pricing also have a bearing on grade pricing. The lower volume cost of structural foam polypropylene is largely a function of its lower density.

Typical applications of polypropylene include:

Injection moldings

- automobile parts including bumpers, dashboards, interior trim, exterior trim, wheel well liners, battery cases, air filter housings
- container caps and closures
- household appliances including washing machine drums, tops, and pump housings, dishwasher spray arms, tumble dryer ducts, electric jug kettles, toaster housings, iron handles and housings, coffee-maker housings
- household goods
- office equipment
- disposable syringes
- chair frames and shells

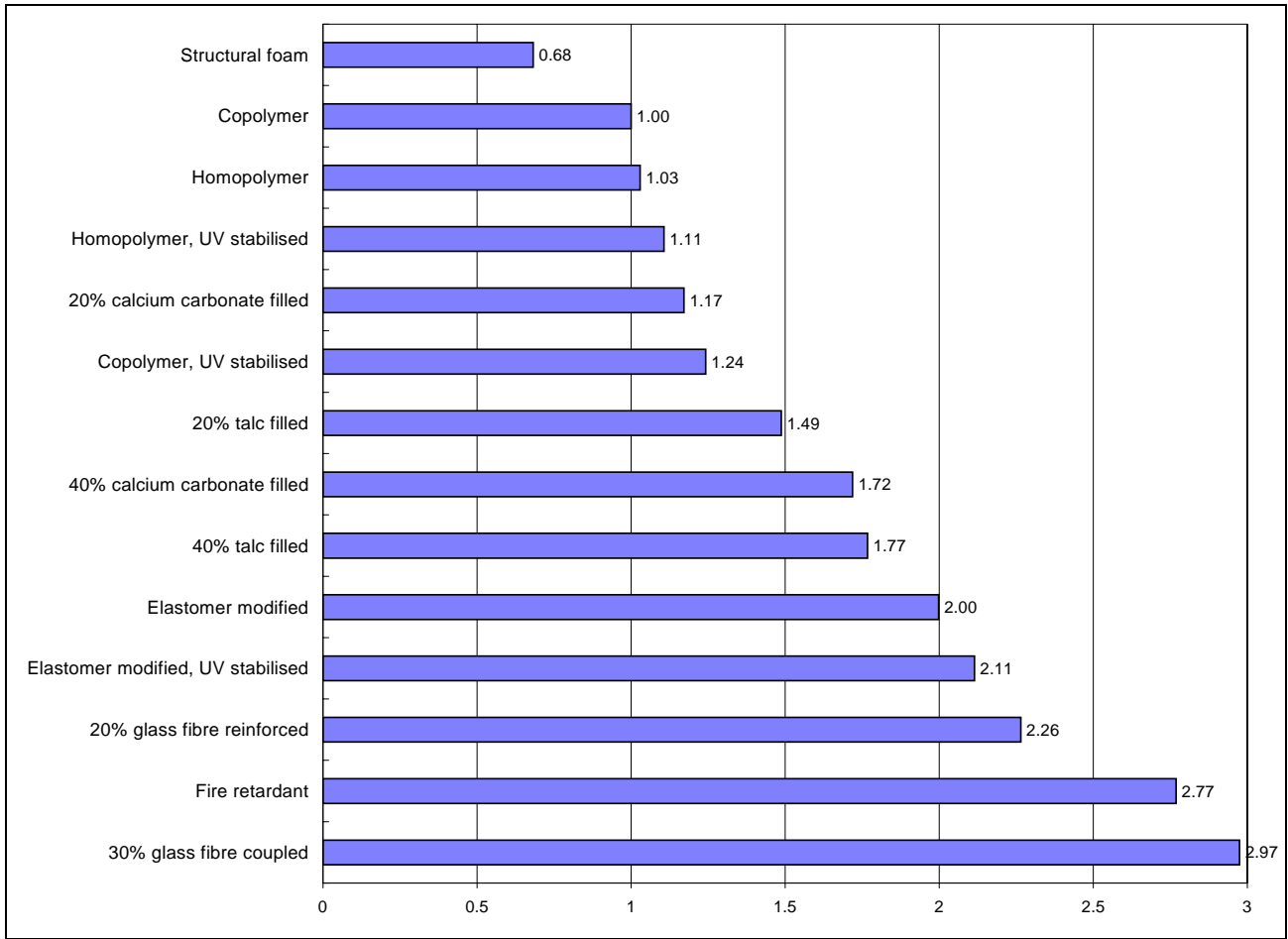


Figure 12.3 Comparative unit volume cost of polypropylenes. [1103]

- buckets, crates, cases
- luggage
- food containers
- paint pots
- video cassette boxes
- toys

Blow moldings

- containers for cosmetic and detergent products
- bottles for products including sauce, ketchup, non-carbonated drinks
- automotive parts including air ducts, overflow bottles
- Thermoformings
- food packaging including yogurt pots, margarine tubs

Extruded film and sheet

- stationery products
- food packaging
- shrink film
- cigarette packaging
- packaging for clothing, flowers, stationery products
- protective sheet for medical and hygiene use

Extruded pipe and tube

- pipes for residential heating and hot water transport

Textiles

- rope and twine
- decorative ribbons
- carpets
- sportswear
- sports surfaces
- upholstery fabrics
- industrial fabrics
- non-woven materials including carpet backing, disposable overalls, geotextiles
- fibers
- strapping tape

12.1.2 Causes of failure

There are many ways in which a plastics article can fail but until recently it has been difficult to guide designers as to which of a multitude of considerations should most occupy them. Now we can be more specific thanks to a recently published study which classified the causes of failure for some 5,000 failed plastics parts. A key finding is that the vast majority of failures were avoidable. The knowledge to prevent these failures was available, and in most cases was readily available. The fundamental problem was inadequate communica-

tion of the knowledge to those — designers, specifiers, processors — who need to know.

There are two viewpoints on the causes of failure. The phenomenological approach attributes the failure to the physical mechanism that brings it about, for example, heat degradation. The same failure though, could be attributed to the human failing of poor selection of material or an inadequately thought out design specification. This is the human approach. The figures developed in the study [1159] give a good guide (Figure 12.4) to the main causes of failure in plastics parts but it is likely that they underestimate the frequency of “obvious” failures, for example, by impact.

Environmental stress cracking emerges as the most prominent cause of failure in all plastics. For polypropylene, this problem can be disregarded. A major advantage of the material is its apparently complete resistance to environmental stress cracking.

The next most important cause of failure is dynamic fatigue, and this high incidence will probably come as a surprise to a great many of those active in plastics design and processing. Even more surprising is that most plastics fatigue failures occur at low or very low frequencies and after less than 50,000 cycles, in contrast to the high frequencies that we instinctively associate with fatigue. As a semi-crystalline material, polypropylene resists fatigue better than the amorphous thermoplastics.

The third most important effect — static notch fracture — is probably understated in the figures in that many such failures are likely to have been judged obvious and not come under expert scrutiny. The cause is stress concentrations arising at sharp corners or notches and it is a vivid demonstration of

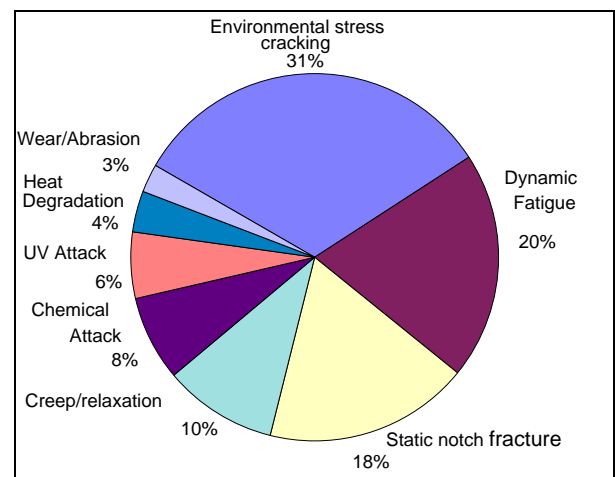


Figure 12.4 Phenomenological causes of failure in plastics articles. [1159]

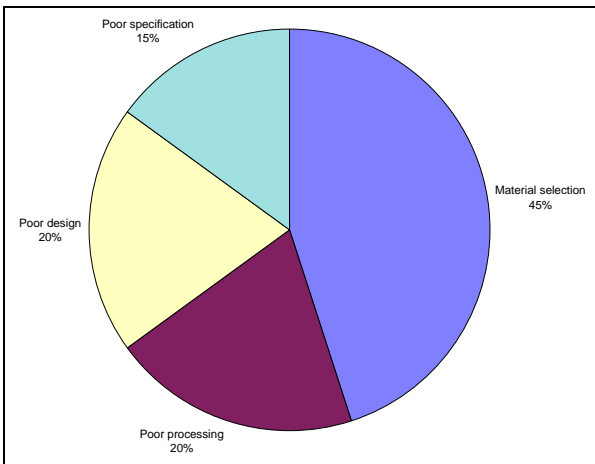


Figure 12.5 Human causes of failure in plastics articles. [1159]

the failure of knowledge communication. The notch effect is very well known but it is continually overlooked, frequently for the very poorest of reasons because it is easier to make the mold that way, or even because it is simpler to draw.

Looking at the same product failures from the human viewpoint, the majority are due to poor selection of the plastics material (Figure 12.5). This is partly because some failures, for example those by chemical attack, are wholly attributable to the material and cannot be alleviated by product design in the narrow sense. The other reason for the problem is the sheer diversity of plastics. There are almost 100 generic “families” of plastics, and the variety can be extended almost endlessly by blending, alloying, and modifying with additives. The total number of available commercial grades of plastics is unknown but it is greater than 20,000 and may approach 30,000. The difficulty of making the optimum choice is obvious.

The problem is mirrored by polypropylene: its versatility means that there are many possible forms and a total of some 3,000 grades available. This diversity is a benefit, but only if designers and processors know how to exploit it. Such diversity demands rational methods of material selection and many software tools have been developed to help with the process. Even so, the crucial choice of material is still too often made on the basis of what has “worked” before to the exclusion of any serious examination of the choices. The high failure rate attributable to poor material choices shows that this practice should no longer be defended or excused in the way it so often has been.

Some 20% of human failures are attributable to poor design. Plastics are very complex materials

and have their own design principles. Those associated with more traditional materials such as metals, stone and timber do not translate. Such materials have been around for thousands of years and so at a shallow level at least, there is some intuitive understanding of what will work. No such intuition yet exists for plastics, most of which are less than 60 years old. Polypropylene itself was unknown before 1953.

Within the normal working range, traditional materials tend to be relatively little affected by temperature and time. The position is quite different for plastics and especially for thermoplastics. Stresses and strains that a thermoplastic can withstand when they are applied slowly may be quite sufficient to shatter it when they are applied rapidly. And a stress that is no problem in the short term may cause the material to deform or creep over a longer period of time. These are instances of the time-dependency of plastics. Similarly, the behavior of plastics will vary greatly within the relatively narrow temperature range of everyday human experience. This range, say from a cold winter’s night to boiling water, will be sufficient to change some plastics from ductile to brittle materials and will have a marked effect on load-bearing performance. These effects illustrate the temperature dependency of plastics. These “non-traditional” effects must be understood to design well with plastics.

12.2 Properties influencing design

12.2.1 Mechanical properties

Like other thermoplastics, polypropylene is a viscoelastic material, consequently its mechanical properties are strongly dependent on time, temperature, and stress. Furthermore, polypropylene is a semi-crystalline material, so the degree of crystallinity and orientation also affects mechanical properties. Additionally, the material can exist as homopolymer, block copolymer, and random copolymer, and can be extensively modified by fillers, reinforcements, and modifiers. These factors too, influence mechanical properties.

The data characterizing the mechanical behavior of plastics falls into three classes. Short-term data (12.2.1.1) describes how the material reacts to stretching, bending, and impact at relatively high rates of strain and short time scales. This is the data that is readily available in manufacturers’ data sheets. It is useful for comparing and ranking grades but is not ideally suited for design work. Long-term

data (12.2.1.2) deals with the way the material progressively deforms or creeps when stress is sustained over a relatively long period. Long-term testing is expensive but the resulting data is far more relevant to the design process than short-term data. The third class — cyclic data — describes how the material responds to fatigue arising from oscillating stresses (12.2.1.3). This class of data too, is directly relevant to the design process.

The data describing the mechanical performance of plastics are determined by standardized tests carried out on prescribed simple sample moldings made under controlled conditions. The structure and morphology of complex commercial articles is likely to be much less uniform than these samples, and this fact must be kept in mind when considering the use of test data. So too, must the relevance of the test to the service condition. For example, if flexure is the key service parameter, try to base the design on flexing data, rather than simple tensile data.

12.2.1.1 Short-term behavior

A number of common short-term tests — tensile strength, elongation at break, strain at yield — are based on the behavior of the material in tension. That of polypropylene follows the general pattern for a hard tough material, showing a relatively high yield strength and high elongation at break (Figure 12.6).

The tensile strength of polypropylene is inferior to that of most other thermoplastics, with the exception of low density polyethylene (Table 12.1). Polypropylene homopolymer has a higher tensile strength than copolymer, and is comparable with high density polyethylene.

Flexural modulus too, is lower than most materials apart from low density polyethylene and some polyamides. Polypropylene copolymer is more flexible than homopolymer. The significance of flexural modulus depends on the particular application. If flexibility is a virtue then a low value

Table 12.1 Mechanical properties of polypropylene compared with other thermoplastics. [1103]

Polymer	Tensile strength (MPa)	Flexural modulus (Gpa)	Elongation at break (%)	Strain at yield (%)	Notched Izod impact strength (kJ/m)
SAN	72	3.6	2.4	3.5	0.02
Polystyrene, general purpose	34	3.4	1.6	1.4	0.02
PET	75	3	70	4	0.02
PVC-U	51	3	60	3.5	0.08
PMMA	70	2.9	2.5		0.02
Polycarbonate	65	2.8	110	7.5	0.7
ABS	47	2.7	8	1.9	0.2
PES	84	2.6	60	6.6	0.084
Acetal	73	2.6	65	8	0.069
PPO	65	2.5	60	4.5	0.16
PBT	52	2.1	250	4	0.06
Polystyrene, high impact	42	2.1	2.5	1.8	0.1
Polyamide 6/6	59	1.6	60	4.5	0.11
Polypropylene homopolymer	33	1.5	150	10	0.07
Polyamide 12	50	1.4	200	6	0.06
HD polyethylene	32	1.3	150	15	0.15
Polyamide 6	40	1.2	60	4.5	0.25
Polypropylene copolymer	25	1.2	300	12	0.1
Polyamide 6/10	58	1.1	300	15	0.09
Polyamide 11	52	0.9	320	20	0.05
LD polyethylene	10	0.3	400	19	no break

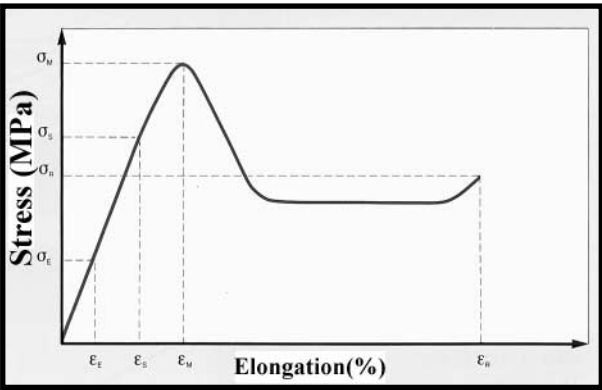


Figure 12.6 Tensile behavior of polypropylene.
 σ_s = tensile stress at elastic limit, ϵ_s = elongation at elastic limit, σ_R = tensile strength at break, ϵ_R = elongation at break, σ_e = elastic constraint, ϵ_e = elastic elongation, σ_M = yield stress, ϵ_M = elongation at yield.

is an advantage. If the application requires stiffness, then an unmodified polypropylene would not be the first choice.

Elongation at break indicates how the material fails in tension. A low elongation figure denotes a brittle rupture, while a high elongation shows that the material responds in a ductile manner. Polypropylene has a high elongation figure, although it is exceeded by low density polyethylene and some polyamides. The elongation figure for polypropylene copolymer is substantially higher than that of homopolymer.

Strain at yield is an indication of the rigidity of the material within its structurally useful range of stress. The comparative ranking of thermoplas-

tics by this criterion is quite similar to that produced by elongation at break, except that there is little difference between the figures for polypropylene homopolymer and copolymer.

Impact strength is the shortest of short-term tests, with the load applied in less than a second whereas the time scale for the other short-term tests is measured in the low minutes. The high rate of deformation induced by near-instantaneous loading causes brittle failure to occur at much higher temperatures than is the case with minute-scale tensile testing. Test specimens are usually notched to concentrate the stress at a predetermined point, thereby overcoming any effect arising from surface irregularities. Impact strength data are a fair way to compare the behavior of different materials but the correlation to drop tests on complex articles is often imperfect. Polypropylene copolymer performs reasonably well in impact although it is substantially outranked by low and high density polyethylenes, ABS, polyamide 6, and “engineering” thermoplastics such as PPO and polycarbonate. The impact performance of polypropylene homopolymer is noticeably less than that of copolymer.

Mechanical properties of polypropylene can be substantially modified by the inclusion of fillers, reinforcements, and modifiers (Table 12.2). Tensile strength is not greatly affected by fillers, nor even by glass fiber reinforcement unless the fibers are chemically coupled to the polymer. Then there is a

Table 12.2 Mechanical properties of polypropylenes with various fillers, reinforcements, and modifiers. [1103]

Polypropylene type	Tensile strength (MPa)	Flexural modulus (Gpa)	Elongation at break (%)	Strain at yield (%)	Notched Izod impact strength (kJ/m)
Homopolymer	33	1.5	150	10	0.07
Homopolymer, UV stabilized	32	1.5	150	8	0.04
Copolymer	25	1.2	300	12	0.1
Copolymer, UV stabilized	24	1.2	300	12	0.08
20% talc filled	32	2.3	15	7	0.03
40% talc filled	30	3.2	8	4	0.03
20% calcium carbonate filled	26	2.0	80		0.05
40% calcium carbonate filled	24	2.8	60		0.04
20% glass fiber reinforced	35	3.8	2		0.08
30% glass fiber coupled	90	6.0	3		0.1
Fire retardant	25	1.8	15	6	0.05
Elastomer modified	23	0.75	350	17	0.5
Elastomer modified, UV stabilized	23	0.75	300	17	0.5
Structural foam	16	0.8	40		0.05

dramatic improvement due to the efficiency with which the tensile load is transferred from the polypropylene matrix to the reinforcing fibers. Flexural modulus, or rigidity, is improved by fillers such as talc and calcium carbonate, as well as by reinforcements. Again, coupled glass fibers are much more effective than conventional glass fibers. Elongation at break is greatly reduced by the inclusion of fillers and reinforcements, but is increased by elastomer modifiers. Impact strength is reduced by fillers but is increased a little by reinforcements and substantially so by elastomer modifiers.

These variations illustrate the “payoff” nature of polypropylene modification; if one property is improved, it is generally at the expense of another. Designers need to bear this in mind. Although not concealed, the downside does not always clearly emerge in the datasheets which are primarily concerned with stressing the performance gains of special grades.

The tensile strength of a material is a measure of its performance limit. It is the breaking point of a brittle material or the yield point of a ductile material. The tensile modulus is an alternative way of characterizing behavior in tension. It is the ratio of stress to strain, and in a proportional material it is known as Young’s modulus. Tensile modulus is a measure of elasticity. Many plastics materials display little or no proportional behavior in tension, so

an “idealized” measure known as the secant modulus is sometimes used. The secant is the slope of a line drawn from the zero stress origin to cut the stress-strain curve at a given strain. These measures can be used to show the extent to which the elasticity of thermoplastics varies with temperature (Figure 12.7).

When shear or torsion is substituted for tension, the equivalent modulus is representative of rigidity and is known as the shear modulus or torsional shear modulus. This too, is strongly affected by temperature. In the graph (Figure 12.8), the upper curves represent torsional shear modulus, while the lower traces represent the logarithmic decrement of mechanical damping. The peaks in the damping curves represent the glass transition temperatures. The curves for the two block copolymers have two peaks, the lower one in each case representing the glass transition temperature of the second component of the block copolymer.

Impact strength increases as the temperature rises and the material becomes more elastic and ductile (Figure 12.9). Typically, the notched impact strength of polypropylenes is more than halved between room temperature and -20°C . Block copolymers retain more impact strength at low temperatures than either homopolymers or random copolymers.

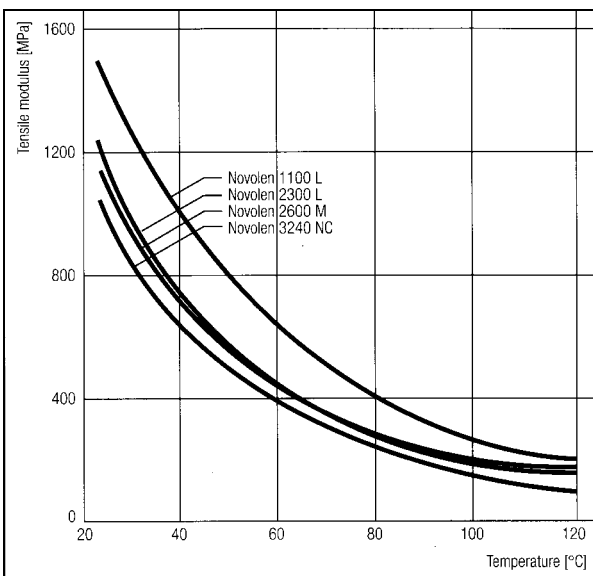


Figure 12.7 Temperature dependence of tensile modulus for BASF polypropylene homopolymer (Novolen 1100L), block copolymer (Novolen 2300L and Novolen 2600M), and nucleated random copolymer (Novolen 3240NC).

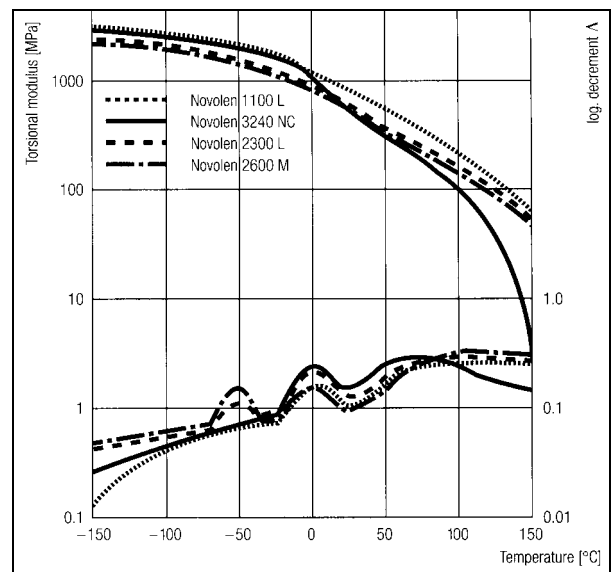


Figure 12.8 Temperature dependence of torsional shear modulus for BASF polypropylene homopolymer (Novolen 1100L), block copolymer (Novolen 2300L and Novolen 2600M), and nucleated random copolymer (Novolen 3240NC).

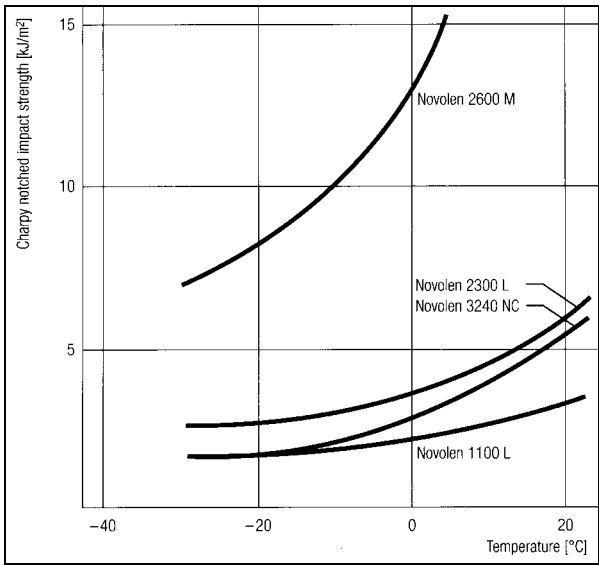


Figure 12.9 Temperature dependence of Charpy notched impact strength for examples of BASF polypropylene homopolymer (Novolen 1100L), block copolymer (Novolen 2300L and Novolen 2600M), and nucleated random copolymer (Novolen 3240NC).

12.2.1.2 Long-term behavior — Creep

The phenomenon of creep occurs when plastics materials are subjected to stress over a relatively long period of time. When the load is first applied, a virtually instantaneous deformation takes place. This is the short-term behavior described by measures such as tensile strength, tensile modulus, shear modulus, and flexural modulus. If the load is maintained, further deformation takes place slowly and this is known as creep, or sometimes as cold flow. Creep is affected by load, temperature, and by the

Table 12.3 Common time intervals for creep testing

Scientific notation (hours)	Normal notation (hours)	Everyday notation
1	1	1 hour
10	10	10 hours
10 ²	100	approx. 4 days
10 ³	1,000	approx. 6 weeks
10 ⁴	10,000	approx. 1 year
10 ⁵	100,000	approx. 11 years

presence of reinforcements, and to a lesser extent by fillers. Creep data, being series data, is almost always displayed graphically and there are a number of methods for doing this. The basic creep curve plots deformation or strain against time for a range of loads or stresses. More common is the isochronous graph in which stress is plotted against strain at a series of constant time intervals (Figure 12.10). A further variant is the isometric graph where stress is plotted against time at a series of constant strain intervals. Alternatively, strain may be plotted against time for a series of constant stress intervals. These various plots are simply different sections taken through the same data surfaces that describe the creep behavior of a particular material. Creep testing is most often performed in tension, but torsion, shear, and flexure data (Figure 12.11) may also be available. The term creep modulus is sometimes used, but it is not a true measure of stiffness. It is a notional time-dependent value which is the

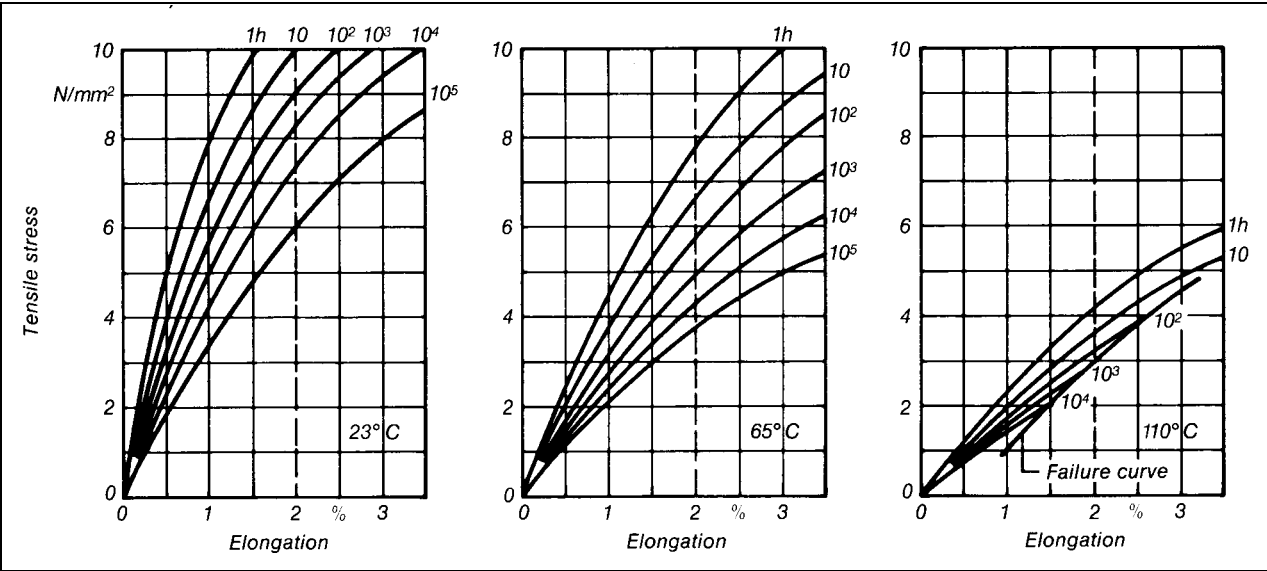


Figure 12.10 Isochronous stress/strain creep plots for Hoechst Hostalen PPH 1050 polypropylene homopolymer.

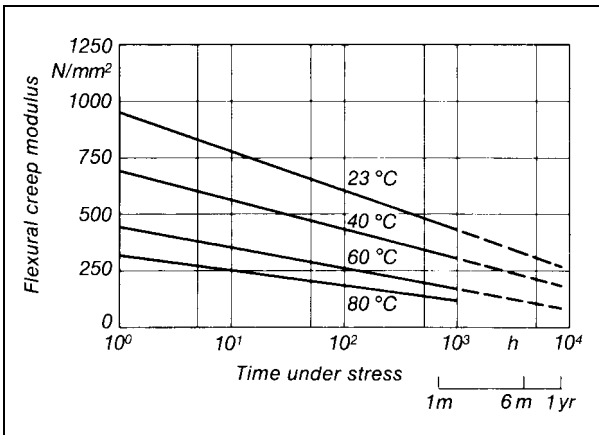


Figure 12.11 Flexural creep modulus for Hoechst Hostalen PPH 1050 polypropylene homopolymer.

ratio of stress to strain (including the instantaneous strain) at any given time, and is also known as the apparent modulus of elasticity (Figure 12.12).

The obvious case of creep in service is that of a constant load producing a gradually increasing level of strain. However, an alternative case is quite common and occurs where features with fixed deformation dimensions such as press fits and springs are in use. In this case, the material is subject to a constant strain and creep is expressed by the decay or relaxation of stress, with a consequent weakening of the spring or press fit. The phenomenon may be described by the relaxation modulus of the material,

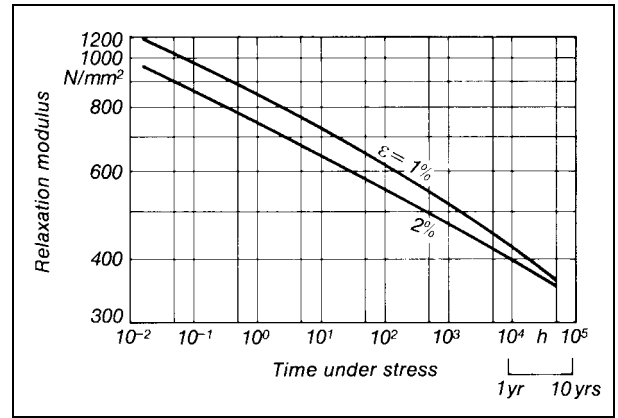


Figure 12.13 Tensile relaxation modulus at 23 °C for Hoechst Hostalen PPH 1050 polypropylene homopolymer.

which is the time-dependent ratio of decaying stress to constant strain (Figure 12.13).

Filled and reinforced grades of polypropylene have a substantially higher creep modulus than basic grades (Figure 12.14). Glass fiber reinforcements are more effective than fillers, and coupled glass fibers perform considerably better than conventional glass fibers. Glass microsphere fillers display only a marginal advantage over the basic grade. The performance of coupled glass fiber grades is particularly outstanding at high temperatures (Figure 12.15).

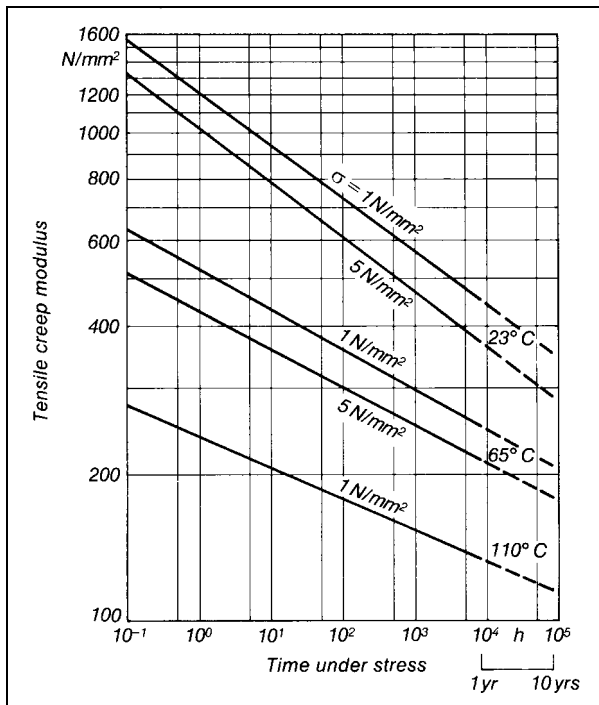


Figure 12.12 Tensile creep modulus for Hoechst Hostalen PPH 1050 polypropylene homopolymer.

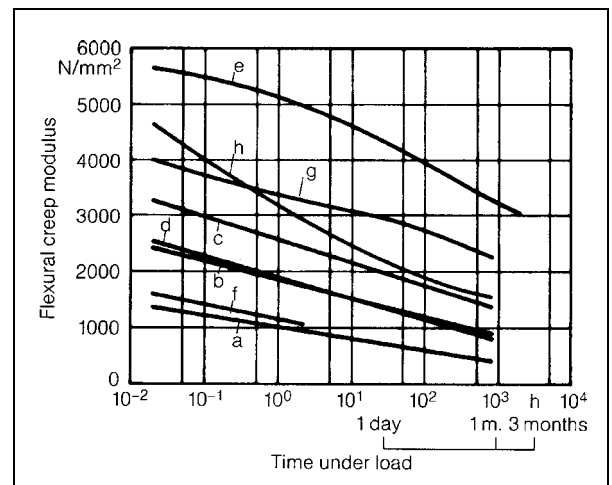


Figure 12.14 Flexural creep modulus at 23 °C of Hoechst Hostacom filled and reinforced polypropylenes. Stress level was 12 N/sq. mm. Key: a = basic non-reinforced grade, b = Hostacom M2 N01 20% talc filler, c = Hostacom M4 N01 40% talc filler, d = Hostacom G2 N01 20% glass fiber reinforcement, e = Hostacom G3 N01 30% coupled glass fiber reinforcement, f = Hostacom G2 N03 20% glass microsphere filler, g = Hostacom G2 N02 20% coupled glass fiber reinforcement, h = Hostacom M4 U01 40% talc filler.

Table 12.4 Dynamic low frequency (0.5 Hz) fatigue stress at 20°C and zero tension of polypropylene compared with other thermoplastics. [1158]

Polymer	Cycles to Failure (MPa)							
	10 ⁰	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵	10 ⁶	10 ⁷
Acetal	70	65	60	55	50	46	34	33
PBT	58	55	51	48	44	41	39	36
Polyamide 6/6	45	43	41	40	38	36	34	33
Polyamide 12	30	28	27	26	25	24	22	21
Polyamide 11	25	24	22	21	19	18	17	16
Polypropylene	27	24	22	19	18	16	15	13
HD polyethylene	25	22.5	20	18	16.5	15	12.5	11
PVC-U	85	76	68	45	23	15	10	6
Polycarbonate	60	58	55	51	48	15	9	6
SAN	60	55	50	45	22	13	9	7
ABS	52	44	37	30	18	12	10	9
PPO	50	40	30	23	17	11	8	5
PMMA	62	48	35	23	14	9	6	4
Polystyrene	18	16	14	12	8	6	4	3

12.2.1.3 *Cyclic behavior — Fatigue*

Materials subjected to cyclic stress — repeated periodic or intermittent reversed loads — fail at a point far below the ultimate figure measured in short-term testing. The phenomenon is known as fatigue. As a rough guide, the fatigue strength of most plastics is only 20% to 30% that of the short-term tensile strength. Fatigue strength decreases with increasing temperature and stress frequency,

and is sensitive to stress concentrators such as notches or sharp corners. Amorphous plastics are far more susceptible to fatigue than semi-crystalline materials such as polypropylene. Heating is a by-product of high stress frequencies, so plastics fatigue testing is often carried out at relatively low frequencies to minimize the temperature effect.

Despite this, evidence is emerging that plastics are being tested at a frequency too great to describe fully the fatigue performance. Fatigue is a common cause of failure in plastics parts, but where these failures have been examined, it has emerged that most occurred at low or very low frequencies and after relatively few cycles, typically less than 50,000. This is not the scenario that designers instinctively associate with fatigue and it does mean that we must give far more attention to cyclic or on/off aspects of product performance in the design process. An air-line filter bowl illustrates the point. The bowl was subjected to pressure-on, pressure-off stress reversals less than ten times per day but that was still sufficient to cause a fatigue failure after a few years in service.

Most published fatigue data for polypropylene and other thermoplastics has been measured by testing at frequencies of 10 Hz or 30 Hz, but some measurements are available at the more revealing rate of 0.5 Hz (Table 12.4, Table 12.5).

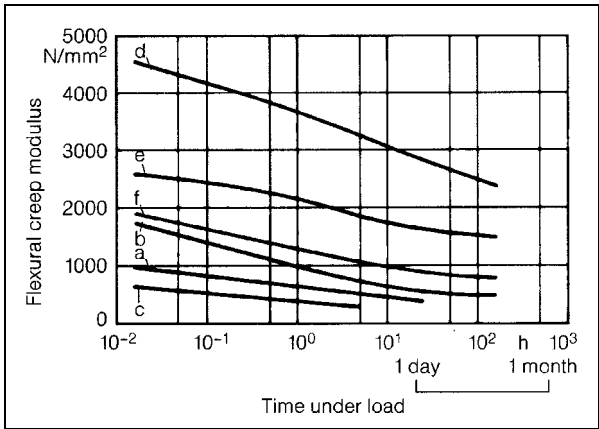


Figure 12.15 Flexural creep modulus at 80°C of Hoechst Hostacom filled and reinforced polypropylenes. Stress level was 5 N/sq. mm. Key: a = Hostacom M2 N01 20% talc filler, b = Hostacom M4 N01 40% talc filler, c = Hostacom G2 N01 20% glass fiber reinforcement, d = Hostacom G3 N01 30% coupled glass fiber reinforcement, e = Hostacom G2 N02 20% coupled glass fiber reinforcement, f = Hostacom M4 U01 40% talc filler.

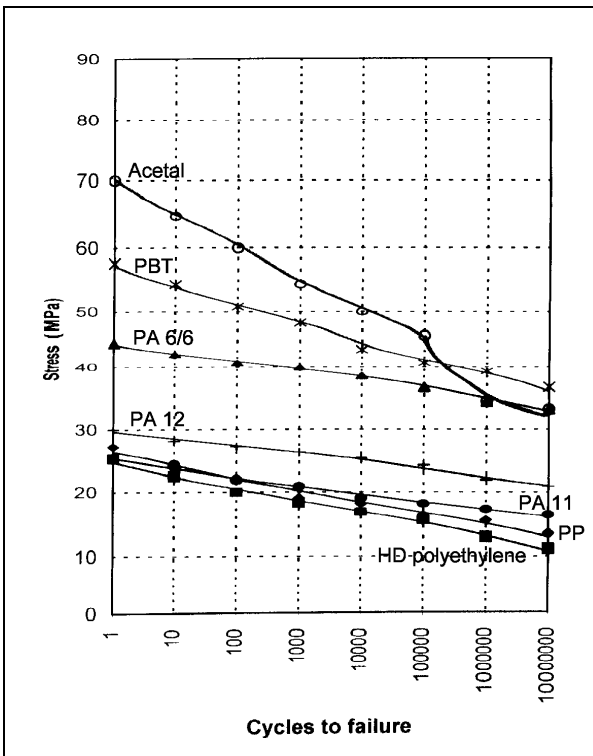


Figure 12.16 Low frequency (0.5 Hz) fatigue performance of polypropylene compared with some other semi-crystalline thermoplastics. [1158]

The figures (Figure 12.16, Figure 12.17) and tables (Table 12.4, Table 12.5) expose a characteristic difference in the fatigue performance of semi-

crystalline plastics compared to amorphous plastics. The fatigue strength of semi-crystalline materials such as polypropylene declines in a substantially linear manner when plotted on a logarithmic cycle scale. The curve for amorphous materials on the other hand, show a distinct “knee” or transition zone which is followed by a very rapid deterioration in performance. The knee represents a transition from ductile to brittle failure and is often excluded from published fatigue curves that typically have a start point of 10^5 cycles. The effect can have surprising results. For example, there are circumstances in which the fatigue performance of polypropylene is superior to that of polycarbonate. Bearing in mind the relative perception of the two materials, this is not a result that one would readily anticipate.

In low frequency fatigue, polypropylene performance declines at about the same rate as other semi-crystalline thermoplastics with the exception of acetal and PBT, where the slope of the curve is rather greater. In other words, the relative strength rankings of the materials are largely maintained throughout cyclic performance. This means that polypropylene has no particular advantage or disadvantage of fatigue resistance when compared with other semi-crystalline materials but does share with them a general advantage over amorphous thermoplastics.

Table 12.5 Dynamic low frequency (0.5 Hz) fatigue strain at 20°C and zero tension of polypropylene compared with other thermoplastics. [1158]

Polymer	Cycles to Failure (%)							
	1 ⁰	1 ¹	1 ²	1 ³	1 ⁴	1 ⁵	1 ⁶	1 ⁷
Polyamide 6/6	3.75	3.58	3.42	3.33	3.17	3.00	2.83	2.75
Polyamide 11	2.78	2.67	2.44	2.33	2.11	2.00	1.89	1.78
PBT	2.76	2.62	2.43	2.29	2.10	1.95	1.86	1.71
Acetal	2.71	2.52	2.33	2.13	1.94	1.78	1.32	1.28
Polyamide 12	2.14	2.00	1.93	1.86	1.79	1.71	1.57	1.50
Polypropylene	2.25	2.00	1.83	1.58	1.50	1.33	1.25	1.08
HD polyethylene	2.00	1.80	1.60	1.44	1.32	1.20	1.00	0.88
Polycarbonate	2.14	2.07	1.96	1.82	1.71	0.54	0.32	0.21
PVC-U	2.83	2.53	2.27	1.50	0.77	0.50	0.33	0.20
ABS	1.93	1.63	1.37	1.11	0.67	0.44	0.37	0.33
PPO	2.00	1.60	1.20	0.92	0.68	0.44	0.32	0.20
SAN	1.67	1.53	1.39	1.25	0.61	0.36	0.25	0.19
PMMA	2.14	1.66	1.21	0.79	0.48	0.31	0.21	0.14
Polystyrene	0.60	0.53	0.47	0.40	0.27	0.20	0.13	0.10

Table 12.6 Suggested design safety factors for polypropylene. [1004]

Failure type	Safety factor for static stress	Safety factor for intermittent stress	Safety factor for dynamic stress
Fracture	2–3	2–3	1.5–2
Permissible deformation	1.2	1.2	1.2
Instability	>3	>3	>3

Fatigue data are usually published in the form of Wöhler (or S-N) curves (Figure 12.18, Figure 12.19). The Wöhler curve simply plots stress or strain amplitude on a linear scale against cycles to failure on a logarithmic scale. The Smith diagram (Figure 12.20) depicts fatigue endurance.

12.2.1.4 Safety factors

The time and temperature dependent behavior of thermoplastics, together with the limitations of published data, makes it necessary to use generous safety factors when designing. The recommended safety factors for polypropylene apply to typical components but it would be wise to scale up for

severe service and for applications where a high degree of risk is attached to component failure.

12.2.2 Thermal properties

Polypropylene is a thermoplastic, that is to say it softens when heated and hardens when cooled. It is hard at normal ambient temperatures, and it is this that allows the thermoplastic property to be exploited in economical processing techniques such as injection molding or extrusion. The softening point, or resistance to deformation under heat, of a thermoplastic limits its service temperature range. The upper permissible limit may be defined as a maximum operating temperature, or as a heat distortion temperature at a given stress level.

The operating range of polypropylene is markedly superior to those of the so-called commodity plastics, and is excelled — sometimes by a substantial margin — only by the far more costly

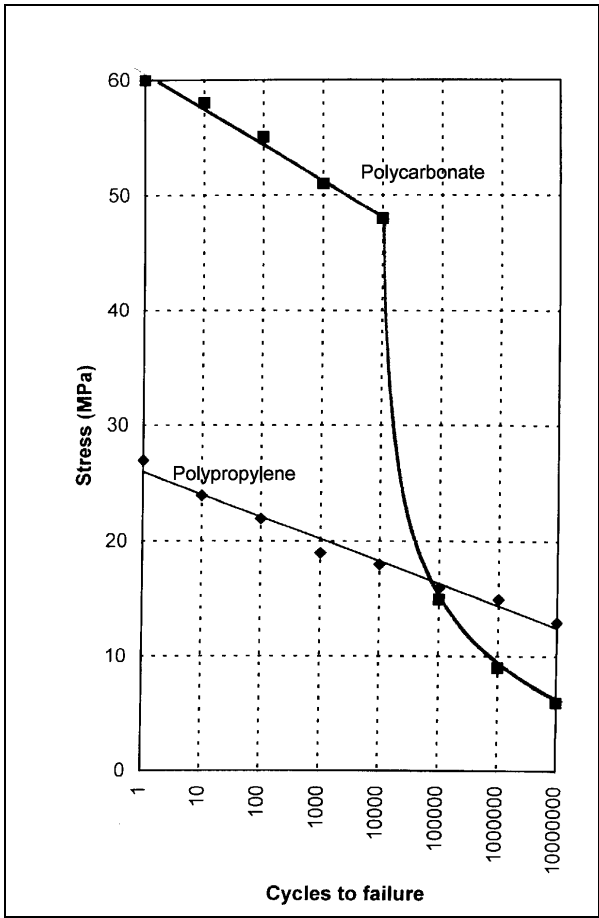


Figure 12.17 Low frequency (0.5 Hz) fatigue performance of polypropylene (semi-crystalline) compared to polycarbonate (amorphous). [1158]

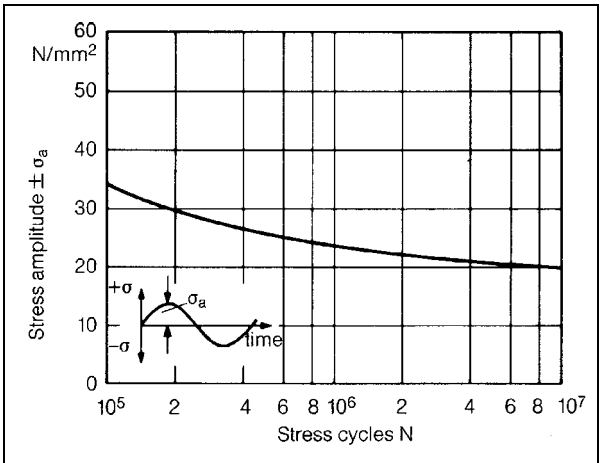


Figure 12.18 Wöhler (S-N) plot for Hoechst Hostacom M2 N01 20% talc filled polypropylene at 23°C and 10Hz.

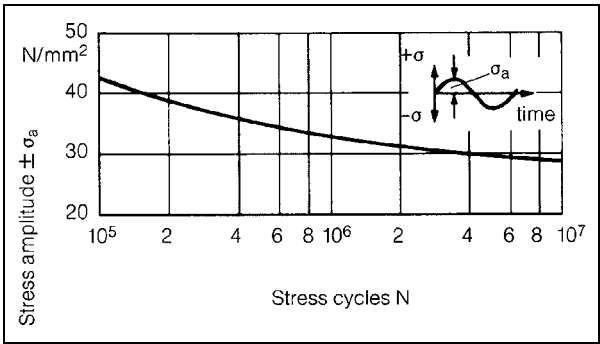


Figure 12.19 Wöhler (S-N) plot for Hoechst Hostacom G3 N01 30% coupled glass fiber reinforced polypropylene at 23°C and 10Hz.

“engineering plastics” (Table 12.7).

If the product has a wide working temperature range, then the coefficient of linear expansion becomes significant and must be allowed for in assemblies. The coefficient for polypropylene is somewhat higher than most commodity plastics but is less than that of polyethylenes.

The operating temperature range of polypropylenes is considerably affected by the use of reinforcements and modifiers (Table 12.8). The heat distortion temperature of talc filled grades is 25°C to 30°C higher than basic grades at the lower stress level, while coupled glass grades extend the figure to 160°C. The effect of talc fillers is far less dramatic for heat distortion temperatures measured at the higher stress level, but coupled glass grades again excel with a performance some 90°C better than basic grades. The heat distortion performance and maximum operating temperature of elastomer modified grades is substantially less than that of

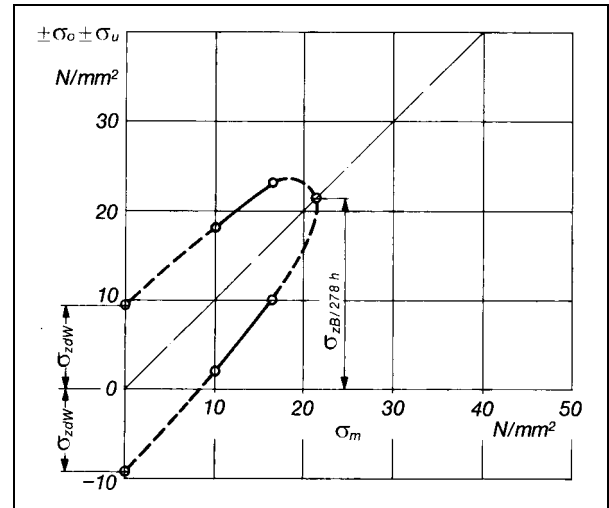


Figure 12.20 Smith diagram for Hoechst Hostalen PPH 2250 polypropylene homopolymer at 23°C and 10 Hz, based on alternating tensile and compressive stress, and repeated tensile stress.

Table 12.7 Thermal properties of polypropylene compared with other thermoplastics. [1103]

Polymer	Maximum operating temperature (°C)	Heat distortion temperature		Linear expansion (mm/°C × 10 ⁻⁵)
		at 0.45 MPa (°C)	at 1.80 MPa (°C)	
PES	180	260+	203	5.5
PBT	120	150	60	12
Polycarbonate	115	143	137	7
PET	115	115	80	8
Polypropylene homopolymer	100	105	65	10
Acetal	90	160	110	11
Polypropylene copolymer	90	100	60	10
Polyamide 6	80	200	80	10
Polyamide 6/6	80	200	100	8
PPO	80	137	129	6
Polyamide 6/10	70	157	66	14
Polyamide 11	70	150	55	9
Polyamide 12	70	150	55	11
ABS	70	98	89	8
SAN	55	96	84	7
HD polyethylene	55	75	46	12
PMMA	50	103	95	7
Polystyrene, general purpose	50	90	80	7
Polystyrene, high impact	50	85	75	7
PVC-U	50	70	67	6
LD polyethylene	50	50	35	20

basic grades. Fillers and reinforcements substantially reduce the coefficient of linear expansion.

The coefficient of linear expansion for a plastics material varies with temperature, unlike those of metals which are substantially independent of temperature (Figure 12.21). For filled and reinforced grades of polypropylene the coefficient also varies with flow direction and orientation.

Polypropylene is a semi-crystalline material consisting of crystalline regions or spherulites contained in an amorphous matrix. These two components behave differently when heated. The amorphous regions soften at a temperature known as the glass transition temperature or T_g . This is not melting but rather a change of state from a brittle or glassy condition to a rubbery or ductile condition. Those plastics with a glass transition temperature in excess of room temperature will fail under stress in a strong brittle manner at room temperature. The glass transition temperature of polypropylene is far below room temperature, so this tells us that the

material will fail in a tough ductile manner at normal temperatures (Table 12.9).

At a higher temperature than the glass transition temperature, the crystallites or spherulites begin to lose cohesion. This is known as the crystalline melting point or T_m . At this point, the conversion to the plastic state is substantially complete. A further

Figure 12.21 Variation of coefficient of linear expansion of polypropylene with temperature (measured in flow direction). Key: a = non-reinforced base grade polypropylene, b = Hostacom M2 N01 (20% talc), c = Hostacom M2 N02 (20% talc, improved impact), d = Hostacom M4 N01 (40% talc), e = Hostacom G2 N02 (20% coupled glass fiber), f = Hostacom G2 N01 (20% glass fiber), g = Hostacom G3 N01 (30% coupled glass fiber), h = Hostacom M1 U01 (10% talc, easy flow), i = Hostacom M4 U01 (40% talc, easy flow), k = pure aluminum. [1004]

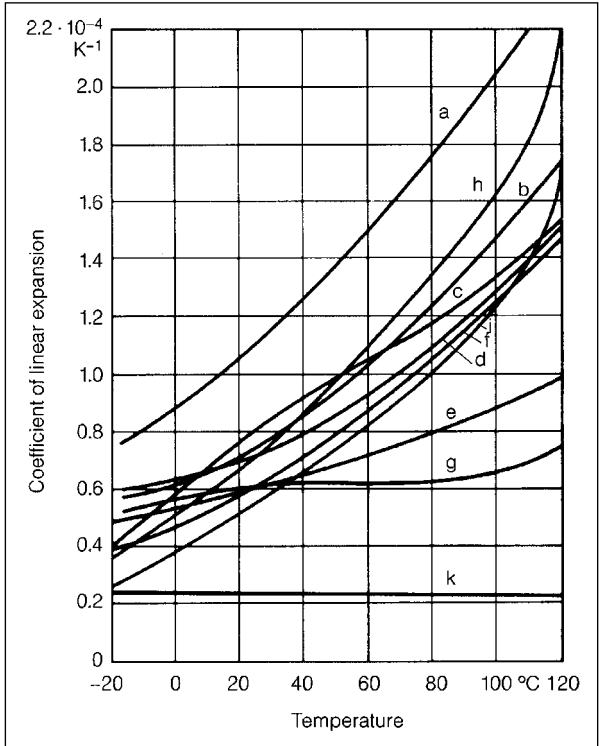


Table 12.8 Thermal properties of polypropylenes with various fillers, reinforcements and modifiers. [1103]

Polypropylene type	Maximum operating temperature (°C)	Heat distortion temperature		Linear expansion (m/m/°C × 10 ⁻³)
		at 0.45 MPa (°C)	at 1.80 MPa (°C)	
Homopolymer	100	105	65	10
Homopolymer, UV stabilized	100	110	57	10
Copolymer	90	100	60	10
Copolymer, UV stabilized	90	100	60	10
20% talc filled	100	130	78	7
40% talc filled	100	130	80	5
20% calcium carbonate filled	100	105	68	6
40% calcium carbonate filled	100	110	71	4
20% glass fiber reinforced	100	122	93	4
30% glass fiber coupled	100	160	150	4
Fire retardant	100	110	70	9
Elastomer modified	90	82	55	11
Elastomer modified, UV stabilized	90	82	55	11
Structural foam	95	72	46	16

rise in temperature will reduce the viscosity of the plastics melt but will not change its state any further. For most plastics, the lower end of the recommended range of processing temperatures will be well above the crystalline melting point, generally by 30°C to 50°C or more.

When the plastics melt is cooled, the crystallites reform but do so at a temperature lower than the crystalline melting point. This temperature is known as the crystallization temperature and it is very much dependent on the cooling rate as well as the presence of fillers, clarifiers and nucleating agents. The crystallization temperature of polypropylene is in the range 100°C to 130°C.

When polypropylene is exposed to high temperatures within its maximum operating temperature, a gradual deterioration takes place. The effect is known as thermal aging. It is an oxidation process and so is related to weathering. All polypropylenes are stabilized against oxidation but special long-term stabilizers are used in grades that must withstand sustained high temperatures or hot detergent solutions. Copper, manganese, cobalt and carbon black additives reduce the resistance of polypropylene to heat aging.

Table 12.9 Glass transition and crystalline melting points of polypropylene compared with other thermoplastics.

Polymer	Glass transition temperature (°C)	Crystalline melting temperature (°C)
Acetal	-50	181
Polyethylene	-33	110–140
Polypropylene	-10	165–176
Polyamide 12	37	179
Polyamide 6/10	40	227
Polyamide 11	46	194
Polyamide 6	50	220
PBT	50	240
Polyamide 6/6	50	265
PET	69	267
Polystyrene	100	240
PMMA	90–105	160
PPO	104–120	-
ABS	80–125	190
SAN	115–125	-
PVC-U	87–135	212
Polycarbonate	150	220
PES	230	-

One measure of thermal aging resistance uses the concept of an induction period. This is the time in days taken for a sample held at 150°C to degrade by a prescribed extent. The induction period for polypropylene homopolymer ranges from 20 to 50 days, depending on the grade formulation. The corresponding range for block copolymers is 50 to 150 days. Random copolymers cannot be characterized by this test because of their lower melting points. The resulting test data make it possible to estimate the service life of polypropylene at elevated temperatures (Figure 12.22).

For example, a polypropylene with an induction period of 20 days would have a service life of about 6 years at 80°C, while one with an induction period of 10 days would have a life of about 1,000 days.

The thermal conductivity of plastics varies with temperature. At service temperatures most are poor conductors of heat, a property that is often exploited in design applications. The thermal conductivity of polypropylene is among the lowest to be found in thermoplastics (Table 12.10).

The thermal conductivity of polypropylene is substantially increased by the inclusion of fillers and reinforcements, particularly by talc (Table 12.11).

12.2.3 Chemical resistance

Polypropylene has a high resistance to chemical attack as a consequence of its non-polar nature. The term non-polar refers to the bond between atoms. The atoms of each element have a specific electronegativity value. The greater the difference between the electronegativity values of the atoms in a bond, the greater will be the polarity of the bond. When this difference is small the material is

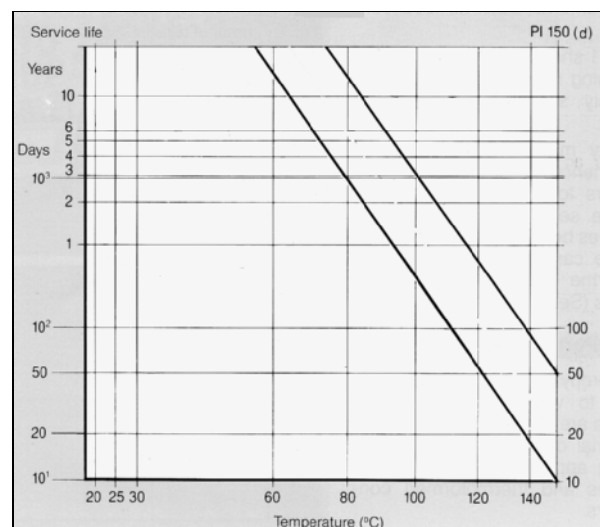


Figure 12.22 Service life of polypropylene. [1016]

Table 12.10 Thermal conductivity of polypropylene compared with other thermoplastics.

Polymer	Thermal conductivity at 20°C (W/m.K)
PVC-U	0.14–0.17
ABS	0.18
PES	0.18
PMMA	0.18
Polystyrene, general purpose	0.18
SAN	0.18
PBT	0.21
Polycarbonate	0.21
Polypropylene	0.17–0.22
Polyamide 11	0.23
Polyamide 12	0.23
Polyamide 6/6	0.23
PPO	0.23
PET	0.24
Polyamide 6	0.29
Acetal	0.25–0.30
LD polyethylene	0.32–0.40
HD polyethylene	0.38–0.51

said to be non-polar. In other words, the solubility of a polymer is related to the forces holding the molecule together, and one measure of this is the solubility parameter δ which is the square root of the cohesive energy density (Table 12.12). Compatibility, that is to say vulnerability, occurs when the solubility parameters of the polymer and solvent are similar. As a very rough guide, the lower the value of the solubility parameter, the more resistant will be the polymer. On this basis, polypropylene rates better than any other melt-processable thermoplastic except polyethylene.

Chemical resistance involves resistance to two principal mechanisms; solution and reaction. Solution is not accompanied by chemical change, and it occurs when a chemical dissolves the polymer. In many cases of solution, polymers are not dissolved outright but simply soften and may also swell. These effects are often reversible when the solvent chemical is driven off. Reaction on the other hand, does involve chemical change and is usually irreversible. All types of chemical attack are more severe at higher temperatures and at higher concentrations of the chemical reagent.

Table 12.11 Effect of fillers on thermal conductivity of polypropylenes. [1004]

Polypropylene type	Thermal conductivity at 20°C (W/m.K)
Polypropylene, unmodified	0.17–0.22
20% talc filled	0.41
40% talc filled	0.56
30% calcium carbonate filled	0.40
20% glass fiber reinforced	0.25
30% glass fiber coupled	0.30

In broad terms, polypropylene is resistant to alcohols, organic acids, esters, and ketones. It is swollen by aliphatic and aromatic hydrocarbons, and by halogenated hydrocarbons. It is highly resistant to most inorganic acids and alkalis but is attacked by strong oxidizing acids and halogens. Contact with copper and copper alloys accelerates oxidation, particularly in the presence of fillers and reinforcements. Table 12.13 gives a rough design selection guide for chemical resistance. No table can account for possible synergy effects when exposure to a mixture of chemicals is expected: there is no substitute for testing in this case.

12.2.4 Electrical properties

Most plastics are good electrical insulators but the properties of polypropylene rank near the best in each of the main measures of electrical performance (Table 12.14). These excellent electrical characteristics are an undoubted advantage, but an

Table 12.12 Solubility parameters of some common plastics. [1101]

Polymer	Solubility parameter δ (MPa ^{1/2})
PTFE	12.6
PCTFE	14.7
Polyethylene	16.3
Polypropylene	16.3
PMMA	18.7
Polystyrene	18.7
PVC	19.4
PET	21.8
Acetal	22.6
Polyamide 6/6	27.8

unwanted side effect is the propensity to build up static electrical charges on the surface. The static charges attract dust and soiling and create a spark potential which although harmless in normal circumstances is a danger in hazardous environments. The development of static charges can be alleviated by the use of anti-static agents.

The electrical properties of polypropylenes are not greatly affected by common fillers, reinforcements, and modifiers (Table 12.15). For the most part, these additives are maintained as discrete bodies within and insulated by the polypropylene matrix, so it is the properties of the latter that prevail. An exception occurs if additives or foreign matter is present at the surface of the polypropylene. In such cases, the surface resistivity will be reduced.

The electrical properties of polypropylene are unaffected by immersion in water and are relatively insensitive to temperature and frequency (Figure 12.23).

There are two occasions when it is desirable to

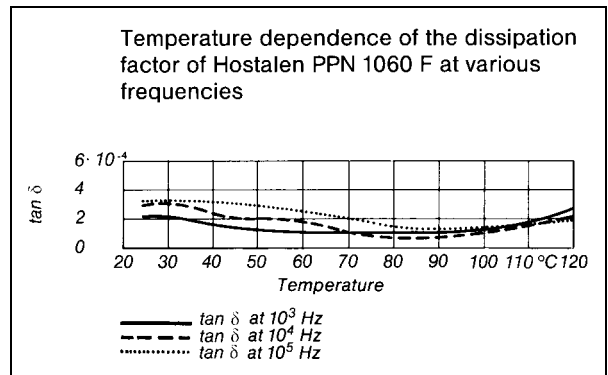


Figure 12.23 The dissipation factor of polypropylene is relatively unaffected by temperature and frequency. [1106]

reduce the dielectric performance of polypropylene and this can be done by the inclusion of special additives. Electrostatic dissipative (ESD) grades are used in circumstances where normal anti-static grades are inadequate or are otherwise unsuitable, for example by virtue of the migratory mechanism. ESD grades would be needed for use in hazardous

Table 12.13 Chemical resistance basic guide for polypropylene. [1148]

REAGENT	70°F (21°C)	120°F (49°C)
Acetic Acid (Glacial)	S	S
Acetic Acid (5%)	S	S
Acetone	S	S
Ammonium Hydroxide (concentrated)	S	NR
Ammonium Hydroxide (10%)	S	S
Aniline	S	S
Benzene	S	NR
Carbon Tetrachloride	NR	NR
Chromic Acid (40%)	S	NR
Citric Acid (1%)	S	S
Cottonseed Oil	S	S
Detergent Solution	S	S
Diethyl Ether	S	NR
Dimethyl Formamide	S	S
Distilled Water	S	S
Ethyl Acetate	S	NR
Ethyl Alcohol (95%)	S	S
Ethyl Alcohol (50%)	S	S
Ethylene Dichloride	S	NR
Heptane	NR	NR
Hydrochloric Acid (Concentrated)	S	S
Hydrochloric Acid (10%)	S	S
Hydrofluoric Acid (40%)	S	S
Hydrogen Peroxide Solution (28%)	S	S
Hydrogen Peroxide Solution (3%)	S	S

REAGENT	70°F (21°C)	120°F (49°C)
Isooctane	S	S
Kerosene	S	NR
Methyl Alcohol	S	S
Mineral Oil, White	NR	NR
Nitric Acid (Concentrated)	NR	NR
Nitric Acid (40%)	NR	NR
Nitric Acid (10%)	S	S
Oleic Acid	S	S
Olive Oil	S	S
Phenol Solution (5%)	S	S
Soap Solution (1%)	S	S
Sodium Carbonate Solution (20%)	S	S
Sodium Carbonate Solution (2%)	S	S
Sodium Chloride Solution (10%)	S	S
Sodium Hydroxide Solution (60%)	S	S
Sodium Hydroxide Solution (10%)	S	S
Sodium Hydroxide Solution (1%)	S	S
Sodium Hypochlorite Solution (4 to 6%)	S	NR
Sulfuric Acid (Concentrated)	NR	NR
Sulfuric Acid (30%)	S	S
Sulfuric Acid (3%)	S	S
Toluene	NR	NR
Transformer Oil	S	M
Turpentine	S	S

Key: S = Satisfactory M = Marginal NR = Not Recommended

environments or in contact with semi-conductor devices. Carbon black is typically used as a conductive filler in ESD grades of polypropylene.

The other reason to increase the conductivity of polypropylene is to provide shielding against electromagnetic interference (EMI) and/or radio frequency interference (RFI). Many electronic and electrical devices such as computers emit signals which may interfere with communications, so regulations now require that these devices be shielded to eliminate or attenuate these signals. The plastics enclosures normally used to house such devices provide no shielding, so secondary measures are needed either in the form of conductive paints on the inner surface, or as a thin sheet metal lining held within the housing. If the plastics housing can be made sufficiently conductive, it will act as a shield so eliminating the cost of secondary measures. Carbon black is not sufficiently conductive, so EMI shielding grades of polypropylene use a range of additives including metal

powders, flakes and fibers, and even composite additives such as nickel-coated graphite fibers.

12.2.5 Environmental stress cracking

One of the major advantages of polypropylene is its apparently complete resistance to attack by environmental stress cracking. The phenomenon is a leading cause of service failure in plastics parts, accounting for perhaps 15% of all observed cases. Environmental stress cracking, often referred to as ESC, causes a stressed plastics part to become brittle and crack when in contact with a wide range of fluids that act as stress cracking agents. It is the combination of stress and fluid contact that causes failure to occur much earlier than either component could achieve in isolation, if at all. It is not easy, other than by experiment, to identify potential stress cracking agents for any plastics material. Solvents will frequently act as stress cracking agents, but some fluids including surfactants that have very little effect in isolation on a particular

Table 12.14 Electrical properties of polypropylene compared with other thermoplastics. [1103]

Polymer	Volume resistivity (log ohm cm)	Dielectric strength (MV/m)	Dielectric constant (1kHz)	Dissipation factor (1kHz)
PES	17.5	16	3.5	0.0021
Polypropylene copolymer	17	28	2.3	0.0005
Polypropylene homopolymer	17	28	2.28	0.0001
Polycarbonate	17	23	3	0.001
HD polyethylene	17	22	2.3	0.0005
PPO	17	21	2.6	0.0004
LD polyethylene	16	27	2.3	0.0003
SAN	16	25	3	0.01
Polystyrene, general purpose	16	20	2.6	0.0002
ABS	16	20	2.8	0.007
Polystyrene, high impact	16	15	2.8	0.0006
Polyamide 12	15	60	3.6	0.05
PMMA	15	25	3.3	0.03
Polyamide 6/6	15	25	8	0.2
Acetal	15	20	3.7	0.0015
PBT	15	20	3.2	0.002
PET	15	17	3.3	0.002
Polyamide 6	14	25	8	0.2
Polyamide 11	14	20	4	0.05
PVC-U	14	14	3.1	0.025
Polyamide 6/10	13	20	4.7	0.09

Table 12.15 Electrical properties of polypropylenes with various fillers, reinforcements and modifiers. [1103]

Polypropylene type	Volume resistivity (log ohm cm)	Dielectric strength (MV/m)	Dielectric constant (1kHz)	Dissipation factor (1kHz)
Homopolymer	17	28	2.28	0.0001
Homopolymer, UV stabilized	16	28	2.3	0.0001
Copolymer	17	28	2.3	0.0005
Copolymer, UV stabilized	17	28	2.3	0.0005
20% talc filled	16	20	2.5	0.002
40% talc filled	16	20	2.6	0.006
20% calcium carbonate filled	15	18	2.6	0.002
40% calcium carbonate filled	15	18	2.8	0.002
20% glass fiber reinforced	16	22	2.6	0.001
30% glass fiber coupled	16	20	2.7	0.001
Fire retardant	14	23	2.5	0.002
Elastomer modified	15	28	2.3	0.0005
Elastomer modified, UV stabilized	15	28	2.3	0.0005
Structural foam	16	26	2.2	0.001

plastics material, are known to be potent stress cracking agents.

It is important to remember that a plastics component need not be externally loaded or stressed to suffer from environmental stress cracking. Manufacturing processes, particularly injection molding, result in residual stresses frozen into the component, and these can be quite sufficient to initiate failure by environmental stress cracking. Neither is it necessary for a plastics part to be immersed in a stress cracking agent to be at risk. Apparently mundane and benign treatments with a range of agents including paints, inks and lacquers, adhesives, plasticizers and lubricants, and rust-proofing fluids are known to result in environmental stress cracking.

Polyethylene, a chemically close relative of polypropylene, does suffer to an extent from environmental stress cracking but polypropylene itself appears to be entirely free of the problem. Failures are known when polypropylene is exposed to strong oxidizing agents such as bleaches. These are sometimes wrongly described as environmental stress cracking but in fact are examples of chemical attack that may be enhanced by stress. The proper term for this phenomenon is corrosion stress cracking or CSC.

12.2.6 Water absorption

The water absorption of polypropylene is very low and is less than that of most other plastics with the

exception of low density polyethylene (Table 12.16). This characteristic is due to the non-polar nature of the material. Polypropylene is water repellent, does not swell in water, and is unaffected in properties and dimensions by changes in relative humidity. In warm humid atmospheres there can be a very small uptake of water, but the effect is entirely due to surface adsorption.

The low water absorption of polypropylene is largely unaffected by fillers, additives, and reinforcements, although a marginal increase does occur with the use of calcium carbonate fillers (Table 12.17).

12.2.7 Permeability

Permeability is a property that assumes importance when a plastics material is provided in relatively thin sections, particularly as films but also as thin-wall injection and blow moldings. It is a measure of the resistance of the material to the transmission of gases and vapors and is of the utmost importance in packaging applications. It implies that the plastics film or barrier separates two distinct and different regimes. Typically, it separates the contents of a package from the normal atmospheric environment. Degradation of the pack contents or the environment may occur if agents can permeate through the barrier in either direction.

Transmission begins when an agent or penetrant dissolves into an exposed barrier surface. This cre-

Table 12.16 Water absorption of polypropylene compared with other thermoplastics. [1103]

Polymer	Water absorption (%)
LD polyethylene	0.01
Polypropylene homopolymer	0.02
HD polyethylene	0.02
Polypropylene copolymer	0.03
Polystyrene, general purpose	0.05
PPO	0.07
PVC-U	0.1
PET	0.1
PBT	0.1
Polycarbonate	0.15
Polystyrene, high impact	0.2
Acetal	0.22
SAN	0.25
Polyamide 12	0.25
Polyamide 11	0.3
PMMA	0.3
ABS	0.3
Polyamide 6/10	0.4
PES	0.43
Polyamide 6/6	1.2
Polyamide 6	1.5

ates a concentration gradient within the barrier and results in diffusion of the penetrant across the thickness of the barrier. The transmission mechanism is completed by evaporation of the penetrant from the second surface of the barrier. Evaporation tends to maintain the concentration gradient and so perpetuates the transmission mechanism. The transmission rate is inversely proportional to the barrier thickness and increases as the temperature rises (Figure 12.24). The two key aspects of permeability are water vapor transmission and gas permeability.

Polypropylene is highly impermeable to water vapor and is bettered in its performance only by specialized packaging materials such as PVDC (polyvinylidene chloride) and CTFE (chlorotri-fluoroethylene). Biaxially oriented polypropylene performs significantly better than cast film because the orientation of the molecules reduces the intermolecular space available for the diffusion mechanism (Table 12.18).

Table 12.17 Water absorption of polypropylenes with various fillers, reinforcements and modifiers. [1103]

Polypropylene type	Water absorption (%)
Homopolymer	0.02
Homopolymer, UV stabilized	0.02
Copolymer	0.03
Copolymer, UV stabilized	0.03
20% talc filled	0.02
40% talc filled	0.02
20% calcium carbonate filled	0.04
40% calcium carbonate filled	0.04
20% glass fiber reinforced	0.03
30% glass fiber coupled	0.02
Fire retardant	0.01
Elastomer modified	0.02
Elastomer modified, UV stabilized	0.02
Structural foam	0.02

Polypropylene performs less well on gas vapor transmission, although once again it is improved markedly by orientation. Nevertheless, a number of materials are clearly superior, for example as oxygen barriers (Table 12.19).

No thermoplastic emerges as an ideal low permeability film material. A few have excellent resistance to water vapor and gases but are expensive or mechanically weak. Others such as polypropylene have very good resistance to water vapor transmission but are less effective against gases. Still other materials show the converse behavior. For this reason it has become very common to use coextrusion and laminating processes to produce multilayer packaging films in order to combine the advantages of several materials. These multilayer constructions may consist solely of a number of different plastics, or they may include other materials such as paper or metal foil. Polypropylene is commonly used for the outer layers of multilayer films where it confers strength, economy and protection to inner specialized barrier layers.

Biaxially oriented polypropylene (BOPP) is particularly important in packaging, and is the predominant film for biscuit and snack foods applications. The performance is often improved with barrier resin coatings, particularly using PVDC. Consumption of BOPP is growing at some 10% per annum. Typical applications include:

- cigarette packing
- shirt packaging
- flower wraps
- shrink wraps
- biscuit and snack food packages

12.2.8 Food and water contact

Polypropylene itself is intrinsically safe. The base material is generally accepted to be non-toxic and non-carcinogenic. Acute and chronic animal feed trials have revealed no damage attributable to polypropylene, neither has there been any evidence of the material acting as an irritant for skin or mucous membranes. Any worry about using polypropylene for contact with foodstuffs or potable water arises from the use of additives in the material, particularly where there is a possibility of these migrating or leaching. All manufacturers of polypropylene produce grades that are safe to use in food or potable water contact applications. Safety in this context is judged according to regulations that vary from country to country. The leading authorities are the Food and Drug Administration (FDA) for the USA, and the appropriate European Directives for the countries of the European Union. Somewhat different regulations, although with the same general thrust, may be applied by the various national water authorities. Provided that approved grades are used and that compliance is checked with the appropriate national regulations, there will be no difficulty in using polypropylene in contact with foodstuffs or potable water. On the contrary, the material has an important role, in the packaging of foods in particular.

12.2.9 Sterilization

Polypropylene itself has no nutritional value for microorganisms and so is not attacked by them. The material cannot be penetrated by microorganisms unless porosity is present. This is unlikely in polypropylene films thicker than 0.1 mm so

Table 12.18 Water vapor transmission of polypropylene compared with other thermoplastics. [1158]

Polymer	Water vapor transmission at 90% relative humidity (gm/mm ² /day)
CTFE	0.005
PVDC	0.1
Polypropylene (oriented)	0.1
HD polyethylene	0.2
Polypropylene	0.3
LLDPE	0.4
LD polyethylene	0.5
EVOH	0.5–2
PET	0.6
Ethylene ionomer	0.6
PVC-U	1
Polystyrene	3
Polycarbonate	3
Polyamide 6	3
PBT	3
EVA	3
ABS	3
PVC-P	5
Polyamide 6/6	5

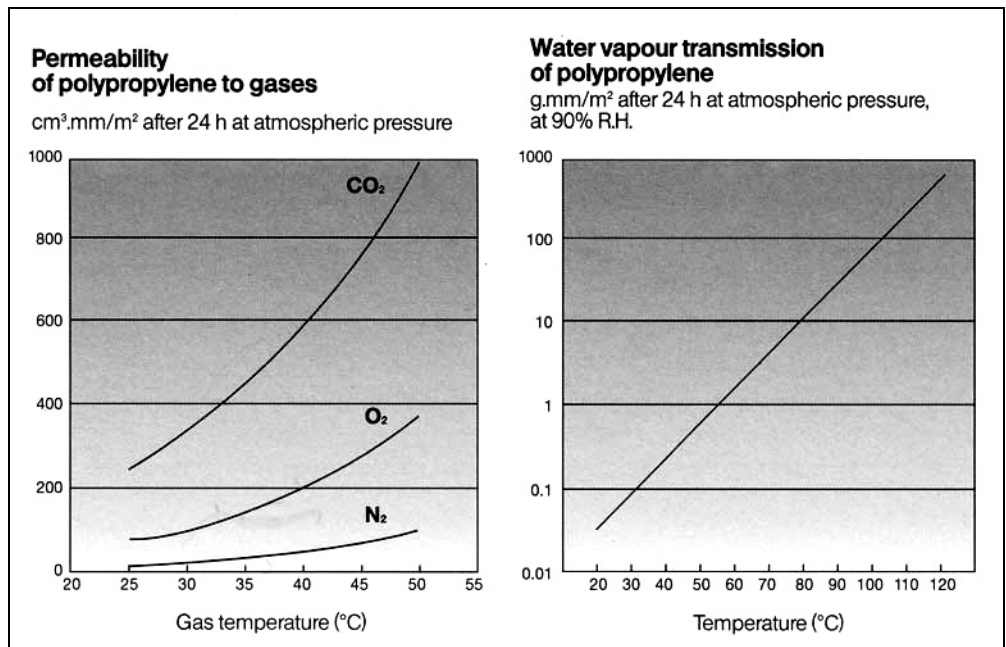


Figure 12.24 Temperature dependence of polypropylene to gas permeability and water vapor transmission rate. [1064]

the material forms an effective barrier against micro-organisms. This property, together with cheapness, versatility, and a fundamentally non-toxic nature makes the material an important contender for medical applications (syringes, packaging) as well as for food use. Both application areas raise the question of resistance to sterilization procedures.

A number of different techniques are in common use:

- irradiation by gamma rays, beta rays, or by electron beam
- gas treatment by ethylene oxide, ethylene chlorohydrin, or ethylene glycol
- heat treatment by steam autoclave or dry oven
- bactericidal treatment by disinfectants and cleaning agents

Of these treatments, gamma radiation is now probably the most important for polypropylene. Gamma rays are more penetrative than electron beam or beta rays, so the method is effective with relatively thick-walled moldings or pre-packaged articles. The high energy treatment is capable of breaking chemical bonds, and in the case of polypropylene, both yellowing and embrittlement effects

are likely to be encountered. To counteract this tendency, the manufacturers of polypropylene have developed specially stabilized grades for medical applications. These radiation stabilizers are an active area of research and solutions are mostly regarded as proprietary. The function of the stabilizer packages is crucial. These special grades of polypropylene are highly successful in medical markets although normal grades would fail through excessive irradiation embrittlement.

The effect of irradiation depends mainly on the dose and the irradiation time. Sterilization is usually performed with a gamma radiation dose of 2.5 Mrad or more. Random and block polypropylene copolymers tend to be less prone to embrittlement than homopolymers.

The once dominant ethylene oxide gas sterilization treatment is now in decline. The material has been declared mutagenic by the US Environmental Protection Agency and special precautions are necessary in its use. Environmental pressure has also focused on the use of CFCs as a carrier gas for the ethylene oxide although this has now been dealt

Table 12.19 Gas vapor transmission of polypropylene compared with other thermoplastics. [1158]

Polymer	Oxygen transmission rate (cm³/mm/m²/atm/day)	Nitrogen transmission rate (cm³/mm/m²/atm/day)	Carbon dioxide transmission rate (cm³/mm/m²/atm/day)
EVOH	>0.01	>0.0015	>0.01
PVDC	0.05	0.1	2
Polyamide 6	0.6	0.35	3
Polyamide 6/6	0.6	0.3	3
PET	2	0.3	6
CTFE	3	0.5	14
PVC-U	7	7	15
PBT	15	3	140
ABS	50	-	150
Polypropylene (oriented)	60	17	200
HD polyethylene	75	20	200
Polypropylene	90	22	250
Polycarbonate	100	13	500
Polystyrene	120	20	400
PVC-P	140	70	900
Ethylene ionomer	150	-	-
LD polyethylene	200	60	700
LLDPE	200	-	-
EVA	300	-	1100

with by the substitution of carbon dioxide or chlorotetrafluoroethane as carriers. A further difficulty is the need to maintain residual gas levels in the sterilized product below guidelines set by the regulatory authorities like the US Food and Drug Administration. Nevertheless, the ethylene oxide gas treatment remains a significant sterilization technique. Polypropylene is generally regarded as substantially unaffected by the treatment.

Steam autoclaving is generally carried out at temperatures of 120°C to 135°C. Polypropylenes are resistant to high temperatures and highly resistant to water, so they are entirely unaffected by autoclaving provided the treatment temperature is kept below the polypropylene softening range. For homopolymers and block copolymers the guideline softening range is 155°C to 165°C. For random copolymers the range is rather lower at 135°C to 150°C.

12.2.10 Transparency and optical properties

The transparency of a material depends on surface smoothness as well fundamental structure. It is defined in terms of two measures — transmittance and haze. A material with good transparency will have high transmittance and low haze. Transmittance is the ratio of transmitted light to incident light. Reflectance — the ratio of reflected light to incident light — is the complementary measure. For an ideal material, the sum of transmittance and reflectance would be unity. For real materials, the difference between unity and the sum of transmittance and reflectance represents light absorbed. Haze is the ratio of incident light passing through the specimen which deviates within a given angle by forward scattering.

The principal factor that mediates the transparency of polypropylene is its semi-crystalline structure. Light is scattered at every boundary between the crystalline and amorphous phases, and so the transparency is directly dependent on the size and concentration of crystalline spherulites in the polypropylene. Random copolymers are more transparent than block copolymers or homopolymer.

The transparency of polypropylene articles can be improved by using molds or dies that impart a high surface gloss and by using process conditions that reduce the size of spherulites. Rapid cooling, coupled with low melt and mold

temperatures, will help to do this. However, low mold temperatures will tend to reduce surface gloss. Polypropylene displays the phenomenon of contact transparency whereby the transparency of a container appears to be improved by contact with the enclosed liquid. The property means that standard polypropylenes are usually good enough for containers where it is necessary to see the liquid level.

The transparency of polypropylenes can be considerably improved by the use of additives that act upon the growth and size of the crystal structure (Table 12.20). These additives are known as nucleators and clarifiers.

12.2.11 Fire behavior

Polypropylene is a combustible material (Table 12.21). It ignites spontaneously at about 360°C and can be ignited from an external source at about 345°C. If the ignition source is removed, the material will continue to burn with a pale luminous flame. The burning material melts and produces burning droplets which have the potential to spread the fire. Burning polypropylene will stick to the skin and cause severe burns.

Fillers, reinforcements, and modifiers have little effect on the fundamental flammability of polypropylene (Table 12.22) but they may have a bearing on the tendency to drip and will also contribute to the products of combustion. However, the flammability of polypropylene can be improved considerably by the use of flame retardant additives.

When polypropylene is pyrolyzed at low concentrations of oxygen, a range of relatively simple hydrocarbons is formed at low and intermediate temperatures. At high temperatures, polycyclic aromatic hydrocarbons are produced. In fires with a relatively low oxygen level, oxygenated organic species are produced, including acrolein which is a severe irritant. The products are less in evidence at higher temperatures and oxygen levels (Table 12.23).

Table 12.20 Optical properties of polypropylene random copolymer. [1016]

Component	Transparency ASTM D 1746 % of value for air	Haze ASTM D 1003 % of value for air
Flask with 0.5mm wall thickness	2.0	17
Injection molded disc 2mm thick - without nucleating agent - with nucleating agent	0.3 18	86 35
The refractive index of polypropylene is 1.49.		

12.2.12 Weathering and light stability

The weathering performance of a material refers to its ability to withstand the natural environment; light stability is only one aspect of this, although a very important one. Weathering is an imperfect term in that it embraces many separate and highly variable effects. Weather testing too is an imprecise science while accelerated weather testing procedures correlate imperfectly with long-term exposure tests. The key factors at work in the weathering process — and these vary widely from one geographical location to another — are:

- solar radiation
- moisture in the form of humidity, condensation or rain
- temperature
- pollutants including ozone, acid rain, and soiling

Table 12.21 Fire behavior of polypropylene compared with other thermoplastics. [1103]

Polymer	Flammability (UL94)	Oxygen index (%)
PVC-U	V0	45
PES	V0	36
Polycarbonate	V2	25
Polyamide 11	V2	22
Polyamide 12	V2	21
PBT	HB	25
Polyamide 6/10	HB	23
Polyamide 6	HB	22
Polyamide 6/6	HB	22
PET	HB	20
PPO	HB	20
ABS	HB	19
PMMA	HB	19
Polystyrene, general purpose	HB	18
Polystyrene, high impact	HB	18
SAN	HB	18
Polypropylene copolymer	HB	17
Polypropylene homopolymer	HB	17
HD polyethylene	HB	17
LD polyethylene	HB	17
Acetal	HB	15

- microbiological attack
- salt water

Depending on the material exposed, many or even most of these factors may be at work simultaneously and perhaps synergistically. The first signs of weathering damage always appear as surface changes or defects but with continued exposure the changes can extend into the body of the material, for example by crack propagation from the surface. Weathering damage then, may entail anything from a slight color change to complete fracture failure.

In the case of polypropylene, microbiological attack is not a problem, neither is the material susceptible to damage by moisture acting in isolation. The principal problem is solar radiation and more specifically, ultraviolet radiation. Some 6% of solar radiation consists of wavelengths below 400nm. This is the ultraviolet region. The mid-range UV-B radiation with a wavelength in the range 290 nm to 315 nm is by far the most damaging. The intensity of UV-B radiation is related to the angle of solar altitude and is at its most severe in regions with high solar altitudes, namely in the tropics. UV-B radiation is completely absorbed by

Table 12.22 Fire behavior of polypropylenes. [1103]

Polypropylene type	Flammability (UL94)	Oxygen index (%)
Homopolymer	HB	17
Homopolymer, UV stabilized	HB	17
Copolymer	HB	17
Copolymer, UV stabilized	HB	17
20% talc filled	HB	17
40% talc filled	HB	18
20% calcium carbonate filled	HB	17
40% calcium carbonate filled	HB	18
20% glass fiber reinforced	HB	17
30% glass fiber coupled	HB	17
Fire retardant	V0	28
Elastomer modified	HB	17
Elastomer modified, UV stabilized	HB	17
Structural foam	HB	17

Table 12.23 Compounds produced by polypropylene at three stages of fire in low ventilation. [1158]

Compound	Fire growth stage (ppm)	Fire steady state (ppm)	Fire decay stage (ppm)
Methane	0.2	◇	◇
Acetylene	2.8	0.6	1.2
Ethylene	2.4	2020.9	899.4
Ethane	5.1	977.5	349.4
Propene	3.3	31.2	3.7
Propyne	◇	25.7	6.2
Methanol	0.5	6.2	12.7
Acetaldehyde	2.7	3.9	2.5
Butene	0.5	18.3	3.1
Butadiene		◇	◇
Cyclobutane		◇	◇
Butane	◇	0.7	0.1
Ethanol			1.7
Acrolein	◇	◇	7.0
Acetone	899.2	216.2	32.5
Cyclopentadiene		23.9	1.1
Pentadiene	◇	◇	◇
Crotonaldehyde	17.2	5.4	7.3

Compound	Fire growth stage (ppm)	Fire steady state (ppm)	Fire decay stage (ppm)
Hexene	0.3	0.4	0.1
Benzene	72.1	809.9	575.1
Cyclohexadiene	0.5	0.1	◇
Heptene	1.2	◇	
Toluene	54.5	56.5	31.6
Octene	1.6	0.4	0.6
Octadiene	◇	0.2	0.1
Xylene	43.0	26.5	15.1
Styrene		32.2	5.6
Nonene	3.1		
Benzaldehyde	12.5	10.7	12.3
Indene	0.4	26.4	2.8
Ethyl styrene	◇	7.1	1.9
Decene	◇	◇	◇
Methyle indene	◇	19.6	2.7
Naphthalene	6.0	204.8	103.0
Methyle naphthalene			◇

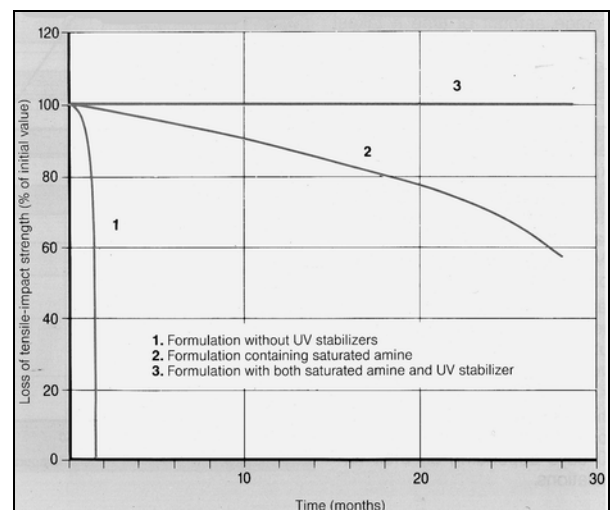
Key: ◇ = present in a concentration too low to measure

the ozone layer at solar altitudes of less than 14°. It is also absorbed by window glass. UV-C radiation (100 nm to 290 nm) is fully absorbed in the ozone layer at all solar altitudes.

Like other polyolefins, polypropylene is highly susceptible to damage by exposure to the UV radiation in sunlight. The surface deteriorates by crazing to a chalky friable material of very low strength. The effect leads to the complete failure of films but in the case of moldings, the damaged surface can be scratched away to reveal a substantially unchanged substrate. Small molded features such as snap-fits and lugs are likely to fracture completely. The mechanism of UV polypropylene failure is akin to oxidation and since crystalline regions are more impervious to oxygen than amorphous regions, the more crystalline nucleated polypropylenes have a somewhat better resistance to UV degradation than less crystalline types. For the same reason, degradation proceeds more slowly in oriented polypropylenes.

Although those pigments that are opaque to UV radiation can give a measure of protection, the fact remains that polypropylene is intrinsically un-

suitable to sunlight exposure unless it is specially stabilized to resist photo-oxidation (Figure 12.25). Even then, there is likely to be some minor deterioration of the surface. The effect can often be noticed on garden furniture and stadium seating. These specially stabilized grades are modified by means of UV stabilizer additives.

**Figure 12.25** Effect of UV stabilizers on polypropylene block copolymer. [1016]

12.2.13 Surface properties

12.2.13.1 Hardness

The surface hardness of polypropylene is less than that of other thermoplastics with the exception of polyethylene (Table 12.24). However, it is sufficient to resist scratching with a fingernail. Hardness decreases as the temperature rises and increases with greater crystallinity. The surface hardness of polypropylene is essentially independent of fillers and reinforcements, although elastomeric modifiers are likely to reduce the figure.

12.2.13.2 Sliding

Polypropylene is rarely used as a sliding or bearing material except in isolated applications such as conveyor belt guide bars for the beverage industry. The friction performance of a few special grades has been improved by means of silicone and/or PTFE additives.

A low coefficient of friction is obviously desirable in a bearing. The coefficient is difficult to determine and depends very much on test conditions. Two cases are important: the plastics material bearing against itself, and the plastics material bearing against a foreign material. In the latter case, polished steel is generally used as a reference

Table 12.24 Hardness of polypropylene compared with other thermoplastics.

Polymer	Ball indentation hardness (N/mm ²)
PET	200
PMMA	180–200
PBT	180
Acetal	150–170
SAN	130–140
Polystyrene, general purpose	120–130
Polycarbonate	110
Polyamide 6/6	100
ABS	80–120
PVC-U	75–155
Polyamide 6	75
Polyamide 11	75
Polyamide 12	75
HD polyethylene	40–65
Polypropylene	36–70
LD polyethylene	13–20

standard. For each case there are two instances. The coefficient of friction observed when moving a body from rest is the static coefficient of friction. The figure observed in a body under steady motion is the dynamic or kinetic coefficient of friction. It is desirable in a bearing material for there to be little difference between the static and dynamic coefficients. The published figures for static and dynamic coefficients must be compared with caution. Dynamic coefficients are often measured at a higher load than static coefficients, and this makes any direct comparison between the figures difficult or impossible. To make matters worse, published figures often omit the test conditions. Consequently, and although it is ostensibly an easy matter, in practice it is difficult to establish from reported figures whether the static coefficient is greater or less than the dynamic coefficient. Instances of both cases have been reported. A material whose static coefficient was the greater would exhibit a “stick-slip” behavior. If the dynamic coefficient was the greater, the behavior would be the less familiar “slip-stick”. For practical purposes, the dynamic coefficient is generally the more appropriate measure (Table 12.25).

Table 12.25 Dynamic coefficient of friction for polypropylene compared with other basic grades of thermoplastics. [1218]

Polymer	Polymer on polymer (Dynamic coefficient)	Polymer on steel (Dynamic coefficient)
PBT	0.24	0.13
Polypropylene	-	0.23
PVC	0.17	0.25
PET	-	0.25
HD polyethylene	-	0.26
Polyamide 6	-	0.26
Polyamide 12	-	0.27
Polyamide 6/6	0.07–0.12	0.28–0.45
Polyamide 6/10	-	0.31
Polystyrene	-	0.32
PES	-	0.32
SAN	-	0.33
ABS	-	0.35
Acetal	0.4	0.35
Polycarbonate	0.37	0.38
PMMA	-	0.4

The performance of a bearing also depends on two other factors, the PV limit and the K-factor. The PV limit describes a limiting value of the product of bearing pressure and sliding velocity. Above this limit the bearing surface fails in some way, generally in the case of a plastics bearing by generating excessive temperatures. Bearing wear is proportional to the product of bearing pressure and sliding velocity. The constant that describes this proportionality is known as the K-factor or wear factor. A good bearing material should have a high PV limit and a low K-factor. Because polypropylene is not used significantly in sliding and bearing applications, quantitative data for the friction, PV limit, and K-factor values is very scanty.

12.2.13.3 Wear

Wear occurs when a plastics material slides or rubs against another body or counterface. There are two main mechanisms for wear. When a plastics materials slides against a smooth counterface, the principal mechanism is adhesive wear. In this case, trace fragments of the plastics surface bond under frictional heat and pressure to the counterface. When the counterface is rough, abrasive wear occurs. In abrasive wear, trace fragments of the plastics surface are eroded by prominences on the countersurface. This produces debris that may augment the erosion process. Wear is difficult to measure (Table 12.26) and predict, being influenced by a wide range of factors, including:

- temperature
- bearing load
- sliding speed
- sliding distance
- motion — continuous, reciprocating, vibrating
- material of the counterface
- surface roughness of the counterface
- heat transfer
- environmental cleanliness
- external lubrication

Table 12.26 Abrasion resistance of polypropylene compared with other thermoplastics. [1016]

Polymer	Weight loss by abrasion under 1kg load (mg/1000 cycles)
Polyamide	4–7
PVC	12
Polypropylene	18–28
HD polyethylene	25

12.3 Other factors influencing design

12.3.1 Orientation

Orientation is a product of flow and a consequence of long-chain molecules. Orientation effects arise from the fact that the forces of attraction between units in the molecular chain greatly exceed the forces of attraction between adjacent chains. The significance of this is that strength can be maximized by orienting the molecules in a common direction. Concomitant disadvantages are that orientation minimizes strength in the transverse direction and results in anisotropic shrinkage during cooling leading to distortion. Where transverse strength is important, the molecules may be oriented in two orthogonal directions. This is known as biaxial orientation. Molecular orientation can be brought about by melt flow, for example during injection molding or extrusion, or by cold flow during stretching processes performed on monofilament or film. A third type of orientation, that of reinforcing fibers, is also significant. The term orientation is applied indiscriminately to all three phenomena and this can lead to some confusion.

Polypropylene is a semi-crystalline material in the solid state. The regularity of the polymer chain structure allows neighboring chains to form regular or crystalline regions within an amorphous matrix. There is orientation of the polymer chains within a crystalline region, but orientation of one crystalline region with another may be quite random. In the melt state, polypropylene becomes fully amorphous. If it is then formed in a relatively stress-free manner, for example by casting and cooled, the crystalline regions will reform in random orientation. However, because polypropylene and indeed all thermoplastics have high melt viscosities, most melt processes involve high or very high shear stresses and shear rates. The shear rates are generated by polymer flow (Figure 12.26) and have the effect of

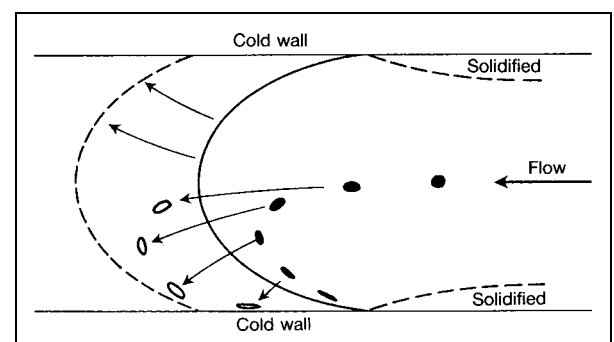


Figure 12.26 Flow of thermoplastics material in a channel.

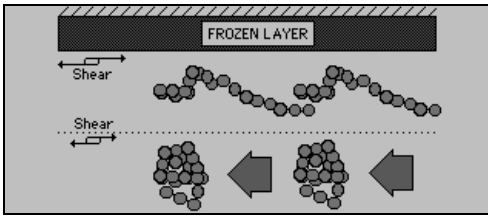


Figure 12.27 Variation of shear rate and orientation across the flow channel. [1175]

orienting the long polymer chains in substantially parallel formations. The degree of orientation is proportional to shear rate, and the extent to which it survives cooling and solidification depends on the rate of cooling. If cooling is very slow, a substantial degree of chain relaxation and disorder is reintroduced. However, if cooling is rapid, as it tends to be in industrial processes, then the orientation is largely retained or “frozen in”.

One instinctively visualizes melt flow orientation as a lining-up of the molecular chains in the direction of flow but this is only partially true. The shear rate varies across the thickness of a flow channel, and therefore so too does orientation. When a thermoplastic flows through a relatively cold mold channel, a thin frozen layer quickly forms against the mold and the remaining flow takes place within this plastics “skin” (Figure 12.27). There is zero shear within the skin layer and little or no orientation. The shear rate varies across the remainder of the flow channel and is at a maximum near the frozen skin. Here there is a high degree of orientation. Shear rates in the center of the flow channel are much lower and so the degree of orientation is much less and may even approach the random state.

The orientation of reinforcing fibers as a result of melt processing follows a similar but not identical pattern. Here the disparity between popular visualization and what really happens can lead to surprising results and design errors. Fiber orientation in and near the frozen skin follows the molecular pattern but in the center of the flow channel where shear rates are low, the fibers instead of being lightly or randomly oriented are actually strongly oriented transverse to the flow direction.

As a generalization, melt flow orientation is an unplanned and largely unwanted side effect of polymer flow. In injection molding it is usually a disadvantage. Extrusion on the other hand, is a steady-state process involving constant geometry, so it is easier to foresee orientation effects and turn them to advantage.

By contrast, cold flow orientation is a pre-meditated action aimed at improving the strength of the material. This is performed by stretching monofilament, tape or film at controlled rates at a temperature below the crystalline melting point of polypropylene, and results in a partial orientation of molecular chains in the direction of stretch. Tensile strength is greatly increased in the direction of stretch while elongation at break is much reduced. Monofilaments and tapes are stretched in a single axial direction; the process is known as monoaxial or uniaxial orientation. Films need strength in all directions and this is usually achieved by stretching in two orthogonal axes. The process is known as biaxial orientation and is of great importance in the production of polypropylene film which is often known as BOPP (biaxially oriented polypropylene) film.

12.3.2 Distinction between homopolymer, random copolymer, block copolymer

Commercial grades of polypropylene are available in three distinct forms — homopolymer, random copolymer, and block copolymer. Homopolymer is produced by polymerizing only propylene monomer. The result is a long chain molecule composed only of propylene groups or units. Copolymer is produced by polymerizing propylene together with minor proportions of secondary monomers, generally ethylene or butene. The result again is a long chain molecule but this time with ethylene or butene units interposed between propylene units. The process can be controlled by polymerization chemistry so that the secondary units are present either as relatively long sequences (block copolymers) or as short sequences or individual units (random co-

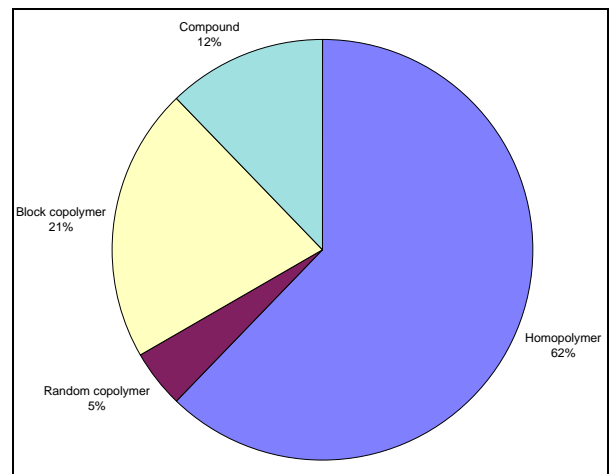


Figure 12.28 Consumption of polypropylene types in Western Europe, 1995. [1219]

polymer). Recent figures for Europe suggest that homopolymer accounts for some 60% of polypropylene consumption while random copolymer occupies a relatively minor though growing market share of about 5% (Figure 12.28).

The three forms overlap to an extent but do have some broad characteristics that help to dictate the optimum material choice. These characteristics are summarized in the table (Table 12.27), while the spread of properties is better illustrated by the graphs (Figure 12.29, Figure 12.30, Figure 12.31, Figure 12.32, Figure 12.33, Figure 12.34).

12.3.3 Additives

The behavior of polypropylene can be extensively shaped and modified by the use of additives. Some of these modifications are essential and are present in all grades of polypropylene, particularly the use of antioxidants to prevent thermal degradation. Others are optional and are used to change the performance in

Table 12.27 Principal characteristics of polypropylene forms

Property	Best choice
Stiffness	Homopolymer
Resistance to high temperature	Homopolymer
Chemical resistance	Homopolymer
Surface hardness	Homopolymer
Impact strength	Block copolymer
Toughness	Block copolymer
strength at low temperatures	Block copolymer
Transparency	Random copolymer
Flexibility	Random copolymer
Sealability	Random copolymer

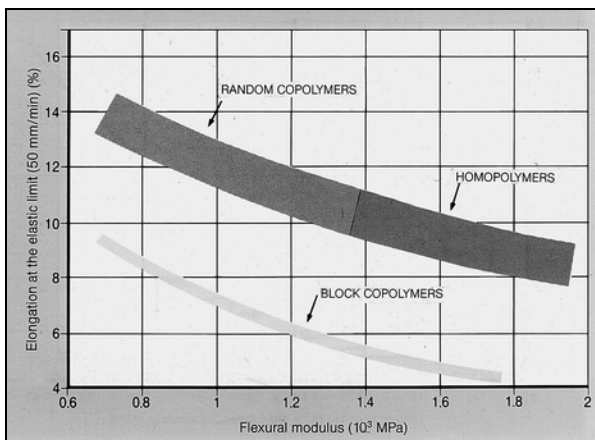


Figure 12.29 Polypropylene forms compared by elongation at elastic limit as a function of flexural modulus. [1016]

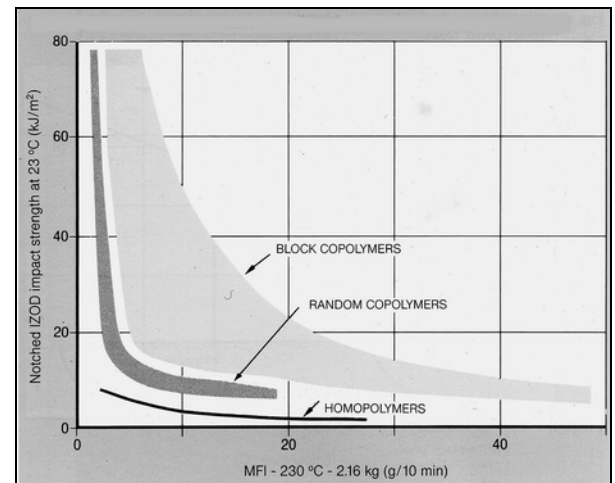


Figure 12.31 Polypropylene forms compared by notched Izod impact strength as a function of melt flow index. [1016]

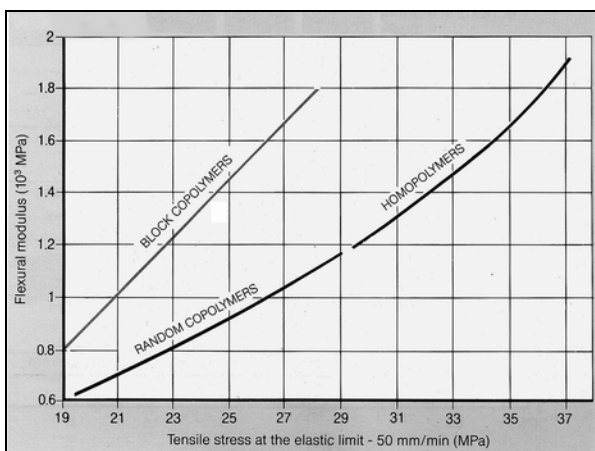


Figure 12.30 polypropylene forms compared by flexural modulus as a function of tensile stress at the elastic limit. [1016]

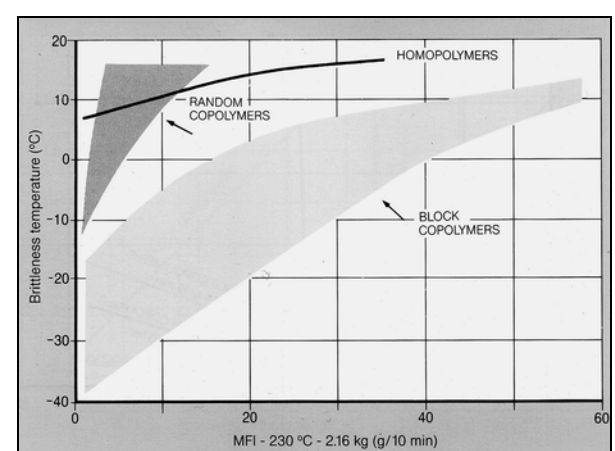


Figure 12.32 polypropylene forms compared by brittleness temperature as a function of melt flow index. [1016]

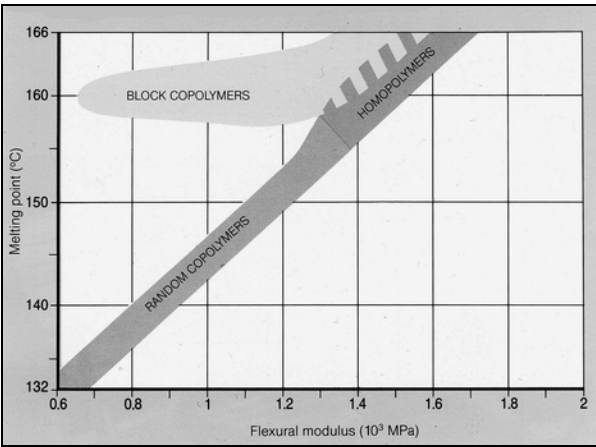


Figure 12.33 Polypropylene forms compared by melting point as a function of flexural modulus. [1016]

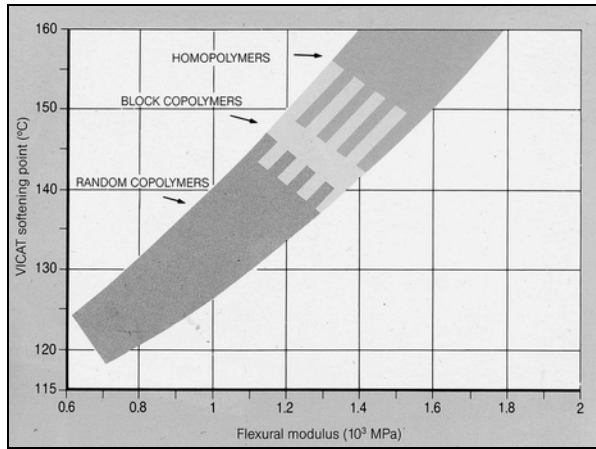


Figure 12.34 Polypropylene forms compared by Vicat softening point as a function of flexural modulus. [1016]

some specific desired aspect, for example to improve mechanical strength or increase resistance to combustion. Such improvements may well be accompanied by a deterioration in another aspect of material behavior. Polypropylene accepts additives well, and this ability to modify the material by such means plays a part in the outstanding versatility of polypropylene as a manufacturing material. Here we draw attention to those aspects of additives that are of particular significance to the designer.

12.3.3.1 Fillers and reinforcements

The primary effect of fillers and reinforcements is to modify the mechanical properties of polypropylene. Side effects, both desirable and undesirable, may crop up in other performance areas of the compound. The effect of a reinforcement or filler depends to an extent on its physical form which can take the shape of a fiber, a platelet, or a sphere. For the purposes of classification, the term

Table 12.28 Effect of form in fillers and reinforcements. [1157]

	Fibers	Platelets	Spheres
	glass, carbon	talc, mica	glass, calcium carbonate, barium sulfate
Tensile strength	↑	↓	↓
Stiffness	↑	↑	↑
Impact strength	↑	↓	↓
Warping	↑	↗	↗

Key: ↑ = increase ↓ = decrease ↗ = marginal

Table 12.29 Normal loading range for fillers and reinforcements in polypropylene.

Filler / Reinforcement	Percentage loading by weight
Talc	10–50
Calcium carbonate	10–60
Barium sulfate	20–50
Mica	10–50
Mineral, unclassified	5–45
Glass fiber	10–50
Glass fiber, coupled	10–40
Glass bead	10–40
Carbon fiber	10–40

sphere embraces three-dimensional granular forms as well as true spheres, while the term platelet refers to any essentially lamellar particle that is thin in relation to its area. The form of the additive has a bearing on the way in which it is incorporated into and interacts with the polymer chain, and this makes possible some broad predictions about the likely effect of fillers and reinforcements on polymer properties (Table 12.28). The terms filler and reinforcement are not precisely defined but reinforcement is generally understood to refer to fibrous forms while filler is taken to mean particulate matter (spheres, granules, platelets).

Many fillers and reinforcements are imperfectly adapted for mixing and dispersion into plastics. Mineral additives particularly are characterized by a high surface area and highly polar nature that makes wetting and dispersion in the polymer difficult. To overcome this, reinforcements and fillers may be modified by means of surface treatments or coupling agents to make them more easily assimilated by the polymer. Surface treatments

aim to lower the surface energy and hence the attractive forces between the additive particles. Coupling agents on the other hand, act on the interface between additive and polymer to create or improve bonding between the two.

Talc

Talc is the most widely used filler for polypropylene and has the effect of improving stiffness, dimensional stability, heat distortion, and creep. A matt surface effect is usually displayed, and there is an adverse effect on impact strength and resistance to degradation by thermo-oxidation. Weldability is also reduced. Talc also acts as a nucleating agent. Talc filled polypropylene is used for:

- automotive under-hood applications, including cooling fans, air ducting, electrical housings
- other automotive applications, including fascia panels, headlight housings
- domestic appliances, including washing machine and tumble dryer components, kettle bodies, housings for irons and toasters, vacuum cleaner internal parts
- power tool housings
- lawn mower parts
- garden furniture

Calcium carbonate

Calcium carbonate has some advantages over talc as an additive for polypropylene. It can be chemically coupled, and is often given a surface treatment, for example with calcium stearate, to ensure good dispersion or to achieve high loadings. Compared with an equal loading of talc, polypropylenes filled with calcium carbonate have better impact strength, elongation at break, and surface quality but are inferior on tensile strength, stiffness, and heat distortion temperature. Calcium carbonate filled polypropylene is particularly used for:

- storage trays
- garden furniture
- camping toilets

Glass fibers

Glass fibers are widely used for reinforcing polypropylene. The effect is to improve tensile strength, flexural modulus, and dimensional stability, and to raise the heat distortion temperature. The drawbacks are reduced elongation at break, a reduction in electrical properties, and a tendency to distortion in injection moldings. Distortion arises from the flow orientation of reinforcing fi-

bers during melt processing. The orientation process is more complex than is generally imagined, and is not uniform throughout the thickness of the part. The end result though, is that any departure from a random orientation of fibers will result in anisotropic properties (properties that vary with the flow direction). It is this variation that tends to cause distortion.

The effect of the glass fiber reinforcement can be considerably enhanced by the use of coupling agents that increase the bond between the fibers and the polypropylene matrix. The effect is to ensure a more efficient transfer of stress from the matrix to the fibers which are consequently more fully utilized. Polypropylenes reinforced with coupled glass fibers have greater stiffness and strength than uncoupled glass types (Figure 12.35, Figure 12.36, Figure 12.37). Typical applications of glass reinforced polypropylene include automotive under-hood applications and headlamp housings and washing machine components.

The length and diameter of the fiber have a bearing on the reinforcing effect. These two considerations are coupled in the aspect ratio — the ratio of fiber length to diameter. The critical aspect ratio is that at which the loaded fiber would be subject to its ultimate tensile strength. The average fiber aspect ratio is usually at least ten times greater than the critical aspect ratio. The situation is complicated by the tendency of compounding and processing to reduce the fiber length by mechanical fracture. Studies show that fiber length after compounding and molding is almost independent of the initial length (Table 12.30). By reducing the fiber diameter, more fibers survive compounding and process-

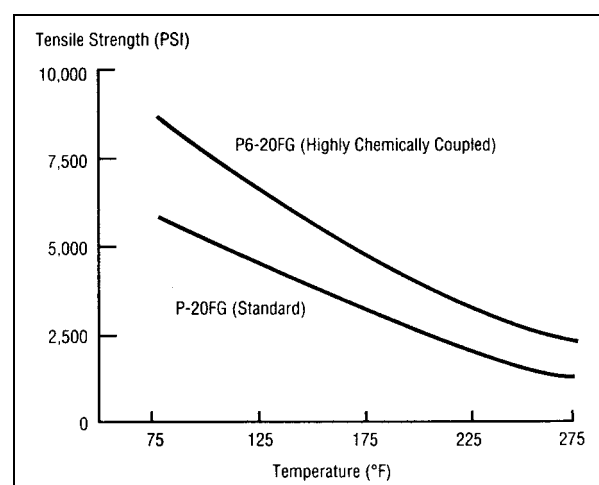


Figure 12.35 Effect of 20% coupled and non-coupled glass fiber reinforcements on tensile strength of polypropylene. [1059]

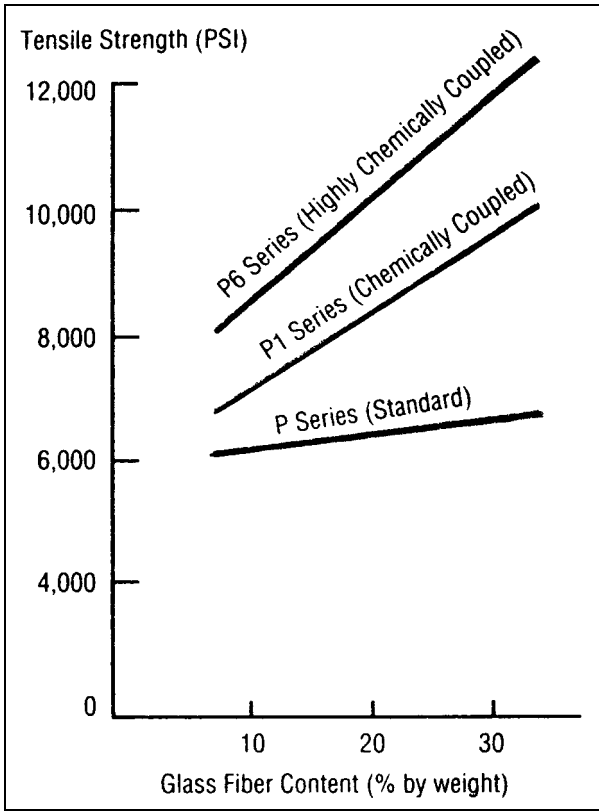


Figure 12.36 Effect of glass fiber reinforcement type and content on tensile strength of polypropylene. [1059]

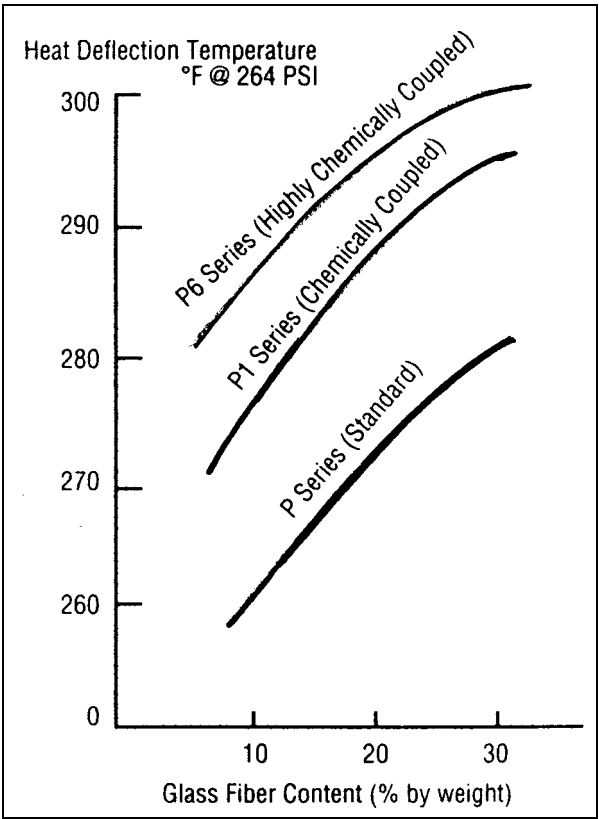


Figure 12.37 Effect of glass fiber reinforcement type and content on heat deflection temperature of polypropylene. [1059]

ing with an aspect ratio above the critical value. For semi-crystalline thermoplastics as a whole, the evidence suggests that tensile strength can be improved by 6% to 10% by reducing the fiber diameter from 13 microns to 10 microns.

Greater improvements can be produced by reinforcing polypropylene with long fibers (Figure 12.38). The pellets are produced by a pultrusion technique that eliminates the fiber damage caused by conventional extrusion compounding. Because the fibers are oriented for pultrusion, it is possible to produce glass loadings up to 75% compared with a practical limit of about 50% for compounded short fibers. The fiber length before proc-

essing is effectively the same as the pellet length, and is typically 10mm to 12mm. Fiber damage and fracture does still occur in processing, but studies show that the effect is much less than had been presumed. Long-fiber reinforced polypropylene challenges for markets currently held by polyamides and other engineering plastics reinforced with short fibers. The properties are comparable while the cost and weight advantage is substantial.

Glass spheres

Glass spheres or beads may be used alone as a re-

Table 12.30 Effect of polypropylene processing on reinforcing glass fibers. [1165]

Input strand length (mm)	Strand length after compounding (mm)	Strand length after injection molding (mm)
3.2	0.76	0.64
4.8	0.76	0.66
6.4	0.99	0.69

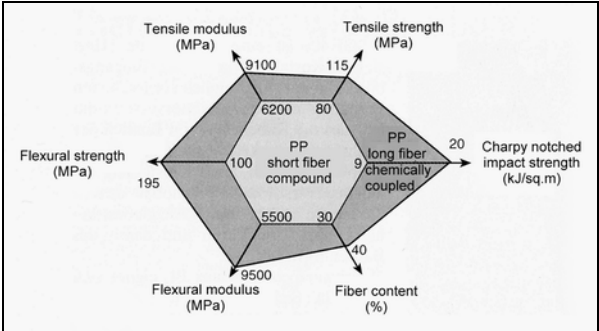


Figure 12.38 Improvement in polypropylene properties produced by long-fiber reinforcement compared with short fibers. [1161]

inforcement but can be deployed in combination with glass fibers. The beads improve stiffness and compressive strength without imparting any directional characteristic. Consequently there is far less tendency for distortion compared with fiber-reinforced grades.

Other fillers and reinforcements

Mica additives can be chemically coupled and surface treated to improve dispersion. They are usually employed to increase stiffness. Wood flour has been used to improve the acoustic property of polypropylene. Wollastonite, a silicate mineral, improves impact strength. Barium sulfate improves stiffness and acoustic property while having relatively little effect on surface finish. Asbestos fibers form a very effective reinforcing agent for polypropylene but the health risk involved in compounding as well as in processing and secondary operations means that the option is no longer available.

12.3.3.2 Nucleating and clarifying agents

Polypropylene is a semi-crystalline material containing ordered crystalline regions that at room temperature typically make up about 60% of the total matter; the remaining material is amorphous. These crystalline regions scatter light passing through the material and the result is the familiar milky translucent appearance that we associate with polypropylene. Both nucleating and clarifying agents act on the crystalline regions to achieve their effects. The primary purpose of a nucleator is to produce a stiffer and faster-cycling polypropylene (Table 12.31), while the aim of a clarifier is to improve transparency. Transparency is particularly desirable in packaging applications.

Nucleating agents cause the crystalline regions to start forming earlier at a higher temperature. The result is a faster and more complete degree of crystallization in which the regions are smaller and more uniform. This produces a polypropylene with increased stiffness and a slight reduction in impact strength. Some nucleating agents also improve the clarity of polypropylene. Moldings made from nucleated grades of polypropylene can safely be ejected from the mold at higher temperatures than standard grades, because of the truncation of the supercooled state. This of course means faster cycle times, but, paradoxically, fast-cycling thin-walled parts may not benefit from nucleation due

Table 12.31 Effect of nucleation on characteristics of polypropylene. [1064]

	Standard polypropylene	Nucleated polypropylene
Crush resistance		✓✓
Impact resistance		
Transparency of homopolymer		✓✓
Cycle time	✓	
Shrinkage, total	✓	
Moldability		✓✓
Extrudability		✓✓
Thermoformability		✓✓

Key: ✓✓ = better ✓ = slightly better = similar

to the risk of premature freezing and short shots in thin sections.

Nucleating agents for polypropylene generally consist of sodium benzoate, kaolin, or talc. Some red pigments are known to interact with sodium benzoate and undergo a an unwanted color change. Random copolymers of polypropylene are naturally clearer than homopolymers and block copolymers, and are not normally nucleated because the effect is to reduce this clarity.

Although clarifying agents also act as nucleators, they operate in quite a different way. Unlike nucleators, clarifiers melt and disperse in the polymer melt. The agents are transparent and have no supercooled phase, so they solidify at their melting point and by doing so they initiate crystallization of the polypropylene. Clarifying agents reduce the size of the crystalline regions, thereby reducing light scattering and increasing transparency. The transparency of the agents themselves also improves light transmission. The modification of crystal structure has the same effect on polypropylene properties and cycle times as a nucleator.

Polypropylene clarifiers are generally derivatives of dibenzylidene sorbitol, and are subject to degradation if melt temperatures exceed 230°C. Degradation increases haze levels; in severe cases the polypropylene may be tainted in smell and taste, and specks may be present in the material. The agent may also form deposits on the mold. Some newer clarifying agents are appearing with a temperature tolerance extending to 260°C.

Low processing temperatures can also be a problem. Transparency is reduced if temperatures are low enough (below about 195°C) to interfere with full dispersion of the clarifying agent. Anti-

static agents are often used with clarifiers to assist in dispersion and to counteract any ejection problems arising from the higher freezing temperature.

12.3.3.3 *Colorants*

In its untreated form, polypropylene is a translucent colorless material and consequently it is capable of being colored to virtually any desired shade. Color is defined in terms of shade, intensity and lightness, and is imparted by means of pigments or dyes. It is an obvious pre-requisite that the colorant must be stable at the melt processing temperature. The quantity required depends on the tinting strength of the colorant. Other considerations include light fastness, chemical compatibility with polypropylene, whether the colorant is suitable for food or medical use, and the health and safety aspects of the colorant itself.

Pigments are insoluble organic or inorganic materials that are dispersed throughout the polypropylene matrix whereas dyes are organic materials that are soluble in the polypropylene. Dyes are easily dispersed throughout the material and result in a more transparent product. On the downside, dyes have a tendency to migrate and are more limited in heat stability and fastness to light. Pigments on the other hand, are available in a wide range of organic and inorganic types, and the chief difficulty is to disperse them evenly throughout the polypropylene. Incomplete dispersion results in agglomerations of pigment particles that cause streaks and uneven shades in the finished article. Organic pigments have more tinting strength and are generally brighter and more transparent than inorganic pigments. However, they are the hardest type to disperse. Organic pigments are generally superior in terms of heat stability and fastness to light.

The dispersion problem, coupled with the need to use more than one colorant to create most shades, has resulted in a number of alternative strategies for coloring polypropylene.

12.3.3.4 *Flame retardants*

Unmodified polypropylene ignites at a temperature of about 360°C and forms burning drips with the potential to spread fire. Flame retardant grades are available with increased fire resistance to V2 or V0 rating on the UL94 scale. The improvement is produced by flame retardant additives that have the dual effect of increasing resistance to ignition and reducing the spread of flame. Unfortunately, there is a severe downside to the use of flame re-

tardants. High concentrations are needed to produce fire resistance and the resulting compound is generally unsuitable for food applications. Retardants substantially reduce the physical properties of polypropylene and generally impose a limit on the melt processing temperature which should not exceed 230°C. Many flame retardants will cause polypropylene integral or 'living' hinges to fail.

12.3.3.5 *Blowing agents*

The function of a blowing agent is to generate a gas during melt processing and thereby to expand the polymer into a cellular structure or foam. Agents are classified as physical or chemical, depending on the way in which the gas is evolved. Physical blowing agents consist of gases that are held in solution in the polymer melt under pressure. When the melt pressure is partially relaxed, the gas comes out of solution. The usual gases are nitrogen and carbon dioxide. A variant of the physical blowing agent is a suitable volatile liquid that vaporizes to form a gas at melt processing temperatures. The chemical blowing agents are solid compounds that decompose at melt processing temperatures; the decomposition product is a gas, usually nitrogen. Not all chemical blowing agents are safe for use in food contact applications. Polypropylenes containing blowing agents can be processed by injection molding and extrusion into products with a density as low as 0.6 g/cm³.

Injection moldings produced from polypropylene containing a blowing agent have a homogeneous and substantially smooth surface skin covering an internal cellular structure. The process is often referred to as structural foam. Extruded foamed sheet, film and tape can be stretched and thermoformed. Typical applications include beverage cups trays for meat products, decorative film and tape, strapping tape, and carpet backing yarn.

12.3.3.6 *Other additives*

Polypropylene formulations may include a range of other additives to deal with specific problems such as static build-up, slip, block, and UV degradation. These impinge on the designer to a lesser extent but there is a need to be aware of the options.

Polypropylene is prone to a build-up of static electric charges that attract dust, make sheets and bags stick together, and cause a spark danger in hazardous environments. Anti-static agents dissipate the static charge, usually by attracting molecules of water to the polypropylene surface. Most

anti-static agents work by migrating to the polymer surface where they can cause a problem with secondary operations such as printing. The difficulty can be overcome by common surface treatments including flaming and corona discharge. However, some non-migratory anti-static agents are available. The migratory types need time to work. Under normal conditions the optimum effect develops two to three days after processing but is then long-lasting and resistant to everyday washing and cleaning. Anti-static agents have a negligible effect on the mechanical, thermal, and chemical properties of polypropylene.

Blocking is the tendency for an adhesive effect to develop between layers of film, particularly where they are under pressure in a stored reel. Slip or the lack of it is the phenomenon of high friction and slip-stick effects occurring between adjacent film layers. It can be a problem both in the manufacture of polypropylene articles and in their end use. Slip and anti-block agents are added to film grades of polypropylene to combat these effects.

In outdoor exposure, polypropylene is susceptible to degradation by the ultraviolet (UV) spectrum of sunlight. The effect resembles that of oxidation and is evidenced by chalking and cracking of the surface, color change, and a reduction in properties. To counteract these effects, UV stabilizers are added to polypropylene compounds intended for outdoor exposure. Many are impaired by the presence of other additives or pigments. This means that it is unwise and undesirable for processors to attempt to further modify UV stabilized grades of polypropylene by compounding in other ingredients. Some UV stabilizers are unsuitable for contact with food although specially stabilized compounds are available for food service.

The impact performance of polypropylene is improved by adding modifying co-monomers during polymerization but can also be adjusted by compounding in modifying elastomeric components. The usual modifier for polypropylene is EPDM rubber at loadings of 10% to 40% by weight. A secondary use of impact modifiers is to “restore” impact properties when these are adversely affected by other functional additives such as flame retardants. Impact modified polypropylenes are particularly used for automotive components, power tool housings, and blow molded containers.

12.3.4 Influence of metallocene technology

A new generation of catalysts using metallocene technology is likely to have a great influence on polypropylene in the future. Metallocene catalysts are also known as single-site catalysts, although not all single-site catalysts are, strictly speaking, metallocenes. Development is very rapid and competitive in this area and it may be some time before the terminology settles down. The key point is that in comparison with conventional multi-sited catalysts, the metallocenes have the capacity to produce polymers with properties that were previously unattainable. Another advantage is that metallocene catalysts are homogeneous with, and are absorbed into the polymer product.

The initial work has been done with polyethylene but a number of producers — Exxon, Hoechst, Fina, Dow, BASF — now have metallocene polypropylenes available in trial quantities. The new materials are becoming known in shorthand as mPP, and are characterized particularly by a very narrow distribution of molecular weight and a lower melting point (Table 12.32). Although the melting point is some 10°C below that of conventional polypropylene, the crystallization temperature is only about 5°C lower. A consequence of the narrow molecular weight distribution is a polymer with a low elongational viscosity and a low melt elasticity. These characteristics are particularly useful in extrusion where they reduce die swell and improve melt draw down for film and fiber operations. Other benefits include improved toughness and clarity better than that offered by nucleated or clarifier-additive grades of conventional polypropylene.

Opinions are divided as to how rapidly metallocene polypropylene will attain commercial prominence. The material is beginning to be employed in fiber and film applications, but there seems to be some way to go before molding appli-

Table 12.32 Comparison of conventional and metallocene polypropylenes. [1137]

Property	Metallocene polypropylene	Conventional polypropylene
Molecular weight distribution	2.0	3.5–6.0
Molecular weight capability	0.01–5000	0.01–1000
Extractables	0.7%	3.3%
Melting point	147–158°C	160–165°C

cations become significant. One industry authority believes that conventional catalysts will continue to dominate polypropylene molding materials for a further 5 to 10 years.

Meanwhile, metallocene materials are emerging as additives and modifiers for conventional polypropylenes. Metallocene-based polyolefin plastomers and elastomers, or POPs and POEs as they are becoming known, are being used to improve the impact strength of polypropylene at low temperature. Another use is to inhibit radiation embrittlement in clarified polypropylene for medical applications. These metallocene-based additives reportedly cause no increase in haze when used with nucleated or clarified polypropylene grades. Other benefits include better weld line strength,

easier flow, increased stiffness, lower shrinkage, and a reduction in thermal expansion. When used with glass reinforced polypropylene, the new additives can provide a balance of stiffness and impact strength that has hitherto been beyond the scope of polypropylene. It seems likely that the use of metallocene POP and POE modified polypropylene grades will develop rapidly both in niche markets and as alternatives to more highly priced polymers.

References for chapter 12:

[1004, 1012, 1016, 1032, 1038, 1049, 1057, 1059, 1063, 1064, 1101, 1102, 1103, 1106, 1137, 1148, 1157, 1158, 1159, 1161, 1162, 1165, 1174, 1175, 1216, 1218, 1219]

13 Processing fundamentals

Processing overview

Extrusion is the most widely practiced process for forming polypropylene, accounting for some 46% of consumption in the USA (Figure 13.1). Of this, the major share is taken by fiber and filament, two forms that are not readily identified with polypropylene in the public consciousness. Film, mainly for packaging and also not popularly recognized as polypropylene, is also a very significant extrusion product. Sheet and profile extrusion is of relatively minor importance. Almost one third of polypro-

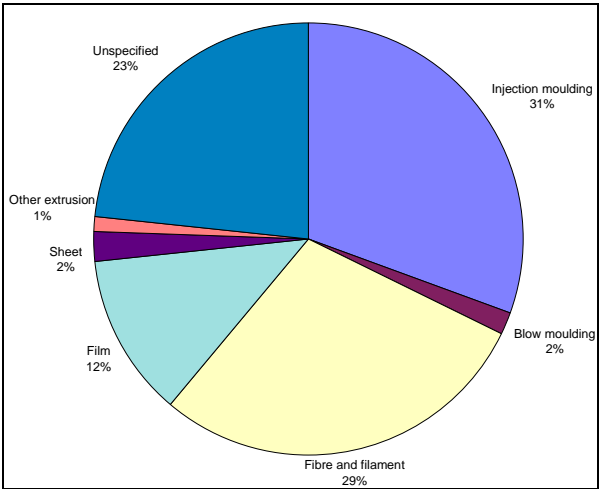


Figure 13.1 Processing methods for polypropylene, USA, 1996. [1216]

pylene is processed by injection molding. Other processes such as blow molding, thermoforming, calendering and so on, probably account for less than 5% of polypropylene consumption. These figures are only a guide; almost a quarter of polypropylene is processed by unspecified methods. Nevertheless, the relative proportions of the various processing methods are probably reliable.

13.1 Properties influencing processing

13.1.1 Flow properties

Polypropylene is formed into articles almost exclusively by melt processes that rely on the flow of the melted material at elevated temperatures. Injection molding, blow molding, extrusion, and thermoforming are all examples of melt processing. An understanding of melt flow is essential for success with these processes. The study of the flow of materials including that of polymers is known as rheology.

The rheology of a thermoplastics melt is complex, being very dependent on temperature and shear rate. This means that the melt viscosity — the characteristic that makes flow easy or difficult — can vary widely in the melt condition. The two key points about the flow of thermoplastics are that the behavior is non-Newtonian and that viscosities are very high. These characteristics are dictated by the long polymer chain molecular structure of the materials. One practical consequence is that considerable force is required to make a plastics melt flow into a mold or through a die. This explains why plastics processing machinery and molds must be so robust and are costly.

To understand and control melt processes, it is necessary to define the way in which melt viscosity changes with temperature and shear rate. The shear rate is a measure of how fast the melt passes through a channel or orifice. A simple fluid such as water has a constant viscosity value regardless of shear rate. This is known as Newtonian behavior in which the fluid can be described fully by a single constant — the viscosity. By contrast, the viscosity of a plastics melt at a constant temperature changes markedly as the shear rate changes. This is non-Newtonian behavior. There is no single viscosity value. The viscosity value for a plastics melt must always be related to the shear rate at which it was determined and strictly it should always be referred to as the apparent viscosity, although this qualification is usually assumed rather than explicitly stated. An important consequence follows. For a viscosity value to be truly useful in determining how a process will turn out, it should be measured at about the same shear rate experienced in the process (Table 13.1). Unfortunately, this is not true of the most popular and widely available measure of melt viscosity, the melt flow rate (MFR) or melt flow index (MFI).

Table 13.1 Process shear rate ranges

Process	Shear rate
Injection molding	High
Blow Molding	Medium to low
Extrusion	Medium to high
Thermoforming	Medium to low
Melt flow rate testing	Low
Capillary rheometer testing	Medium to high

Table 13.2 Approximate relationship between MFR and polypropylene injection molding conditions.

MFR range (g/10 min)	Injection pressure range (bar)	Melt temperature range (°C)
<4	600–1200	240–280
4–10	500–1000	220–250
10–20	500–1000	210 –240
>20	400–1000	200–230

The melt flow rate test is performed at a low shear rate so MFR figures will be at their least inaccurate for medium to low shear rate processes like blow molding and thermoforming, and will be most inaccurate for injection molding. The quoted MFR value is the weight of polymer melt flowing through an orifice in specified conditions, so the higher the MFR value, the lower the melt viscosity and the easier the material will flow (Table 13.2). Even though MFR values are measured at an unrealistically low shear rate, it might seem that the test would accurately rank different materials for comparative ease of flow. Unfortunately, not even this can be guaranteed because of the varying degree of shear dependency shown by different materials and grades. The MFR test owes its continued survival mostly to tradition and the fact that it is cheap and easy to perform.

More reliable viscosity measurements can be made with high-shear rheometers. Material testing is performed at shear rates similar to those experienced during extrusion or injection molding, so the resulting values have a direct bearing on process

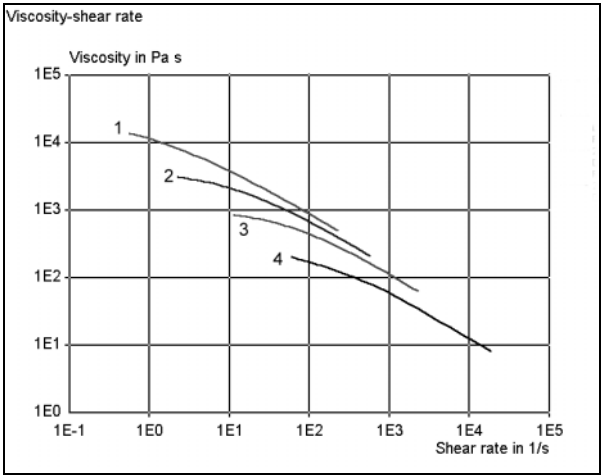


Figure 13.2 Typical viscosity curves at 260°C for some PCD polypropylene grades. Key: 1 = Daplen BHC 5003 (blow molding grade) — MFR 0.4, 2 = Daplen CF 501 (calendar film grade) — MFR 1.1, 3 = Daplen FSC 1012 (block copolymer molding grade) — MFR 5.0, 4 = Daplen PT 551 (thin wall molding grade) — MFR 19.0.

considerations (Figure 13.2). Even then, it is not a simple matter to depict flow behavior. A number of viscosity “models” have been developed to describe this behavior, and while a detailed discussion is beyond the scope of this work, it is as well to be aware of some of these models because they are used in process simulation computer programs that predict the effect of product and control parameters on the end product. The simplest version is known as the power law model. More elaborate and accurate models are based on higher order versions of the power law, or on the Carreau, Cross, or Ellis models. Flow data corresponding to these models is still not widely published but can usually be obtained on request from materials suppliers. Developers of flow simulation software maintain extensive databases of plastics flow data but these are not freely accessible. The situation is due to improve with the announcement that Campus, the free industry-standard materials database, will include rheological data in its next version.

A third type of flow measurement is sometimes available, although its popularity appears to be waning. Spiral flow data is an attempt to relate flow information directly to the injection molding process by using an industrial molding machine to run the tests, in conjunction with a test mold in which a very long graduated flow channel is arranged in a spiral. The disadvantage is that reproducibility be-

Table 13.3 Approximate flow range of polypropylene compared with other thermoplastics.

Polymer	Approximate flow length for 2mm wall thickness (mm)
Polyamide 6/6	810
Polypropylene	250–700
LD polyethylene	550–600
Polyamide 6	400–600
PBT	250–600
HD polyethylene	200–600
Acetal	500
Polystyrene	200–500
PMMA	200–500
PET	200–500
Polyamide 12	200–500
ABS	320
PVC-U	160–250
Polycarbonate	150–220

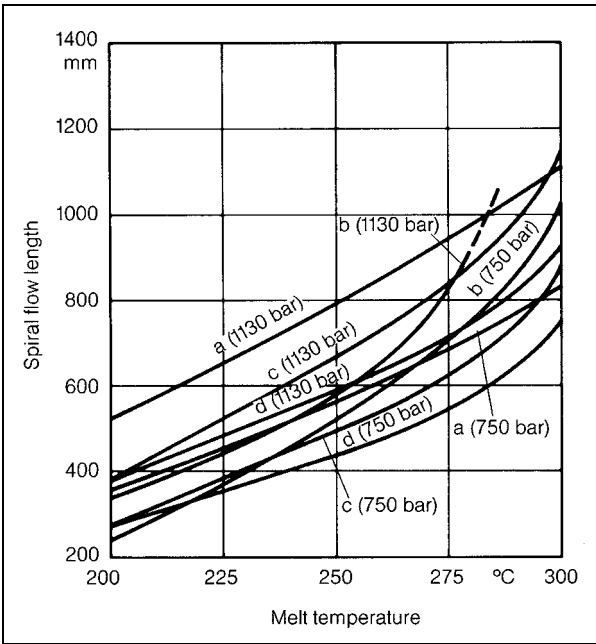


Figure 13.3 Spiral flow length of some reinforced Hoechst polypropylenes at 750 and 1130 bar injection pressure Key: a = non-reinforced base grade, b = Hostacom M4 N01 (40% talc), c = Hostacom G2 N01 (20% glass fiber), d = Hostacom G3 N01 (30% coupled glass fiber).

tween different presses and molds is low. The spiral flow behavior of a thermoplastic is characterized simply by the flow length observed under prescribed conditions of temperature, pressure, and flow rate. Flow length measurements are specific to the test conditions and cannot be extrapolated to

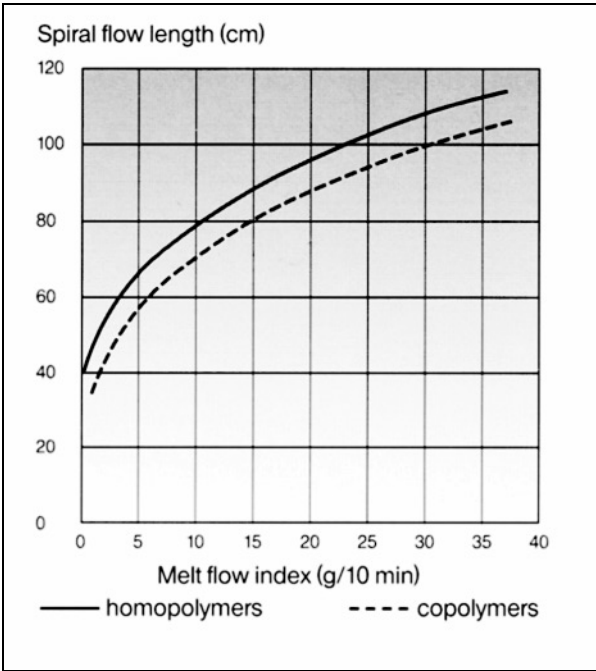


Figure 13.4 Approximate relationship between melt flow index and spiral flow length.

other circumstances. For example, there is no straightforward way to relate flow data taken on a 2 mm thick test mold to a practical molding of a different thickness. However, because the test is performed at process shear rates, it will reliably rank materials for ease of flow at the test condition (Table 13.3). Practical considerations of time and cost make the test unwieldy for exposing temperature and shear dependencies (Figure 13.3).

A wide spread of polymer chain lengths is an inevitable consequence of the polymerization process, and it is this that creates within any polymer a range of molecular weights. The statistical distribution of these molecular weights is known as the molecular weight distribution, or MWD. The sensitivity of polypropylene melt viscosity to shear and temperature is largely dependent on its molecular weight distribution. This distribution can be controlled to an extent so that polypropylene grades may be produced in broad or narrow molecular weight distributions (Figure 13.5). The broad MWD product will be more shear sensitive than a narrow MWD grade (Figure 13.6). This exposes another shortcoming of the melt flow rate test. Broad and narrow MWD polypropylenes can have the same

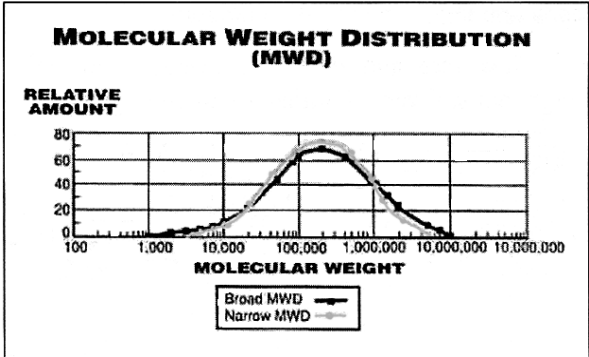


Figure 13.5 Comparison of broad and narrow molecular weight distributions.

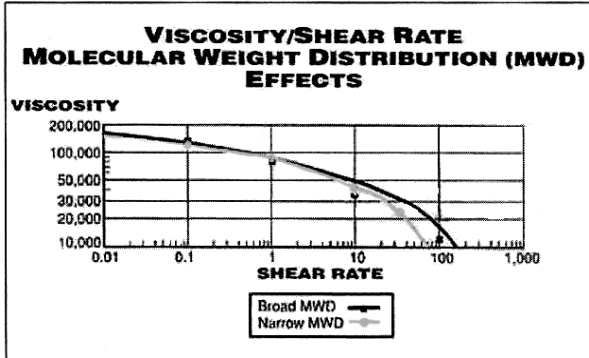


Figure 13.6 Comparison of shear sensitivity for broad and narrow molecular weight distributions.

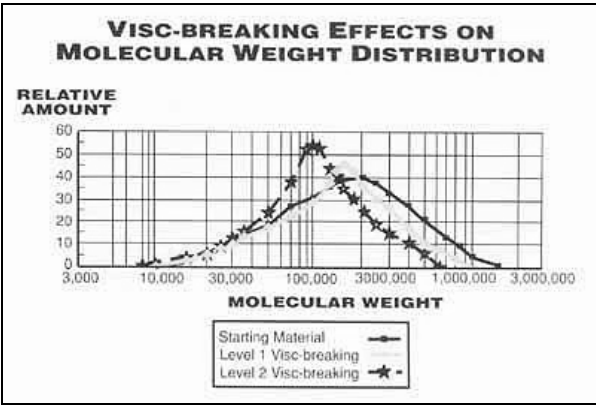


Figure 13.7 Effect of vis-breaking on the molecular weight distribution of polypropylene.

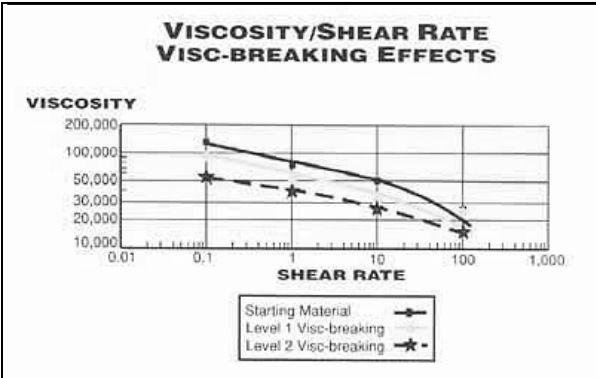


Figure 13.8 Effect of vis-breaking on the melt viscosity and shear sensitivity of polypropylene.

melt flow rate and the same average molecular weight but still vary significantly in processing.

Easier flowing grades of polypropylene can be produced by deliberately promoting chain scission during the production of the polymer. Chain scission involves a breaking of the polymer chains in a mechanism akin to degradation. Unlike degradation, the method results in a predictable and reproducible degree of chain scission. The result is a polypropylene with a narrower molecular weight distribution and a lower melt viscosity (Figure 13.7). The narrower molecular weight reduces the sensitivity of melt viscosity to shear, particularly at higher shear rates (Figure 13.8). Materials produced in this way are known as controlled rheology (CR) grades, or

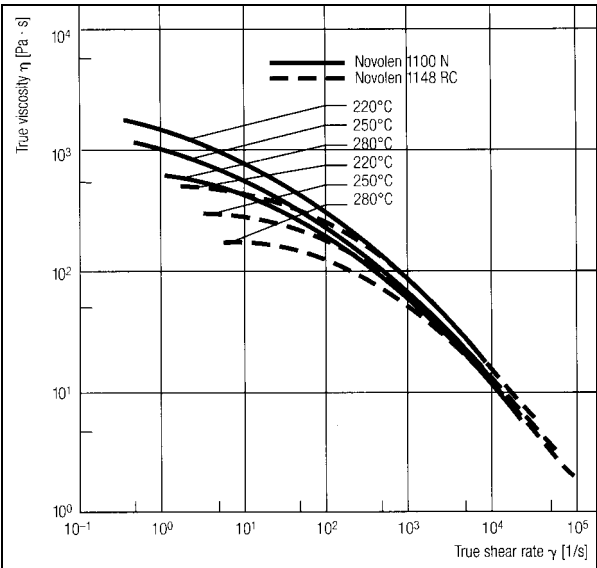


Figure 13.9 Melt viscosity behavior of controlled rheology polypropylene compared with conventional polypropylene. Key: BASF Novolen 100N = conventional homopolymer grade, BASF Novolen 1148 RCX = controlled rheology homopolymer grade.

sometimes as vis-broken (VB) grades (Figure 13.9). Homopolymers, random copolymers, and block copolymers are all available in controlled rheology versions.

Controlled rheology grades of polypropylene are generally used for fiber and film production where the improved draw-down results in faster production rates, and for injection molding parts that are difficult to fill, or where it is important to minimize distortion or warpage (Table 13.4).

13.1.2 Thermal properties

The melt processing of thermoplastics involves first heating the material to a point at which it can be made to flow, then cooling it again to a temperature at which the formed object is stable. This requirement constitutes a major energy demand in the forming process, and is central to the efficiency and economy of the process. It is a common perception that thermoplastics are difficult to heat and even harder to cool, and that this is particularly true of polypropylene. The perception is a

Table 13.4 Principal characteristics of controlled rheology polypropylenes

Property	Advantage	Disadvantage
Narrower molecular weight distribution	Reduced warpage	Reduced melt strength
	More uniform shrinkage	Reduced stiffness
	Improved draw-down performance	Less reduction in viscosity at high shear rates
Shorter polymer chains	Reduced melt viscosity	

sound one, and a study of thermal characteristics will show why this is so.

The heat energy or heat content of a system is a function of the mass of a material, its specific heat, and the temperature change. The quantity is often referred to as enthalpy. The heat energy to melt a thermoplastic is therefore proportional to the difference between its melt temperature and room temperature. Theoretically, the heat energy to be removed in cooling, in the case of a molding, is the difference between the melt temperature and the mold temperature. In practice, the component can usually be ejected at a higher temperature, and only a region near the surface need be at this temperature, so the heat to be extracted is considerably less.

The heat energy involved in heating and cooling varies considerably from one polymer to another (Table 13.5). An additional consideration is the fundamental difference between amorphous and semi-crystalline plastics. For semi-crystalline materials, the heat requirement for melting includes an additional quantity for melting the crystalline structure. This is known as the latent heat of fusion of the crystalline structure. At 670 J/g, the melting heat requirement of polypropylene is exceeded only by HD polyethylene and poly-

amides 6 and 6/6. It is more than double that of polystyrene, and is considerably greater than the energy requirement for materials with much higher melt temperatures, such as PPO, polycarbonate, and PES. The cooling requirement for polypropylene is even more severe. Only HD polyethylene is more demanding. These thermal characteristics have a direct bearing on processing. They mean for example that cooling for a polypropylene mold must be much more efficient than for most other plastics.

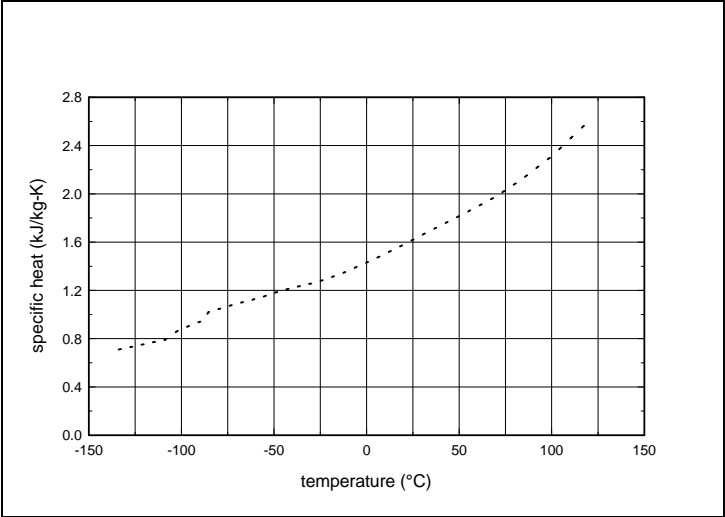


Figure 13.10 Temperature dependency of specific heat of polypropylene (PP)

Table 13.5 Process heat requirements of polypropylene compared with other thermoplastics.

Polymer	Melt temperature (°C)	Mold temperature (°C)	Heat required to melt (J/g)	Heat removed on cooling (J/g)
PES	360	150	391	242
PET	275	135	556	305
Polystyrene	200	20	310	310
Acetal	205	90	555	345
Polycarbonate	300	90	490	368
ABS	240	60	451	369
PMMA	260	60	456	380
PPO	280	80	551	434
Polyamide 11	260	60	586	488
Polyamide 12	260	60	586	488
LD polyethylene	200	20	500	500
Polyamide 6	250	80	703	520
Polyamide 6/6	280	80	800	615
Polypropylene	260	20	670	670
HD polyethylene	260	20	810	810

The need is often overlooked and it is this that is responsible for the commonly experienced difficulty of overheating cores and pins.

The specific heat (Figure 13.10) and thermal conductivity of plastics vary greatly with temperature. So indeed does density. These variations are not brought out in data sheets that deal only with solid properties, and are not widely appreciated by plastics processors. It is still difficult to obtain information about the thermal properties of plastics in the melt state, even though this is important for plastics process calculations. A plot of enthalpy against temperature shows the extent of the variation and also clearly differentiates between amorphous and semi-crystalline materials. The enthalpy curve for the semi-crystallines shows a distinct discontinuity or “knee”. The rapid increase in enthalpy at this point corresponds to the latent heat of crystalline fusion. The curve for an amorphous materials shows no such discontinuity. The enthalpy curves give a direct read-out of the approximate heat energy to be added or removed when heating or cooling a plastics material, and deserve to be more widely distributed.

The table (Table 13.6) gives guideline spot

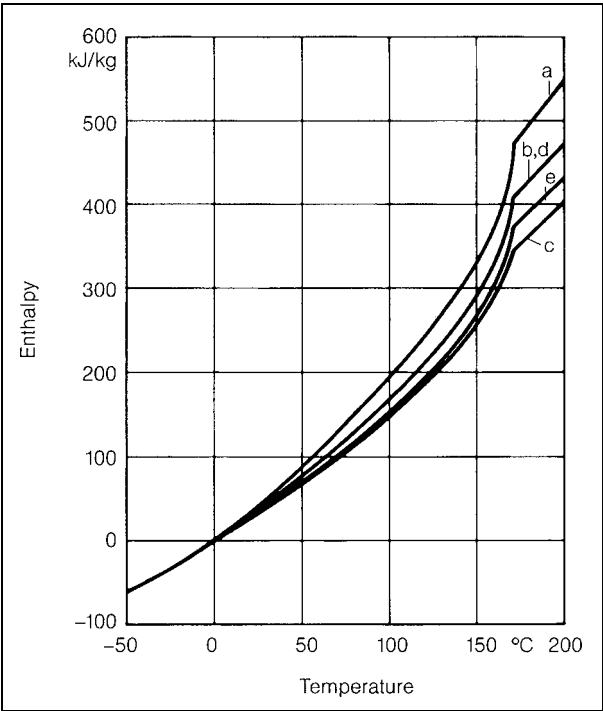


Figure 13.11 Enthalpy of melt for some reinforced Hoechst polypropylenes. Key: a = non-reinforced base polypropylene, b = Hostacom M2 N01 (20% talc), c = Hostacom M4 N01 (40% talc), d = Hostacom G2 N01 (20% glass fiber), e = Hoechst Hostacom G3 N01 (30% coupled glass fiber).

Table 13.6 Approximate thermal melt properties of polypropylene compared with other thermoplastics.

Polymer	Melt density (g/cm ³)	Specific heat of melt (kJ/kg-K)	Thermal conductivity of melt (W/m-K)	No-flow temperature (°C)	Freeze temperature (°C)	Latent heat of crystalline fusion (kJ/kg)
PES	1.48	1.3	0.15	240	225	0
PVC-U	1.15	1.5	0.14	120	85	0
PET	1.15	1.6	0.20	230	190	-
Polystyrene	0.88	1.8	0.13	130	95	0
Polycarbonate	1.01	1.8	0.19	180	150	0
SAN	0.92	1.9	0.15	140	100	0
PMMA	1.01	2.0	0.15	140	110	0
PPO	0.92	2.0	0.15	160	140	0
ABS	0.89	2.1	0.15	140	105	0
PBT	1.12	2.1	0.18	220	190	180
Acetal	1.22	2.5	0.13	150	140	0
Polyamide 6	0.95	2.7	0.12	220	215	200
Polyamide 6/6	0.97	2.7	0.13	250	240	250
Polypropylene	0.85	2.7	0.19	140	120	235
LD polyethylene	0.79	3.2	0.28	110	98	180
HD polyethylene	0.81	3.3	0.29	120	100	190

values for the thermal properties of thermoplastics melts. In reality the values for density, specific heat, and thermal conductivity are temperature-related variables. The latent heat of crystalline fusion is zero for amorphous polymers because the phenomenon is absent. Freeze temperature is the point at which the material becomes a solid. The no-flow temperature is not a fundamental property. Rather it is a useful concept that has been introduced in flow calculations to compensate for shortcomings in viscosity models at low temperatures near to solidification. Effectively, it is the temperature at which the viscosity of a not quite frozen polymer is held to be infinite.

Reinforcements and fillers tend to reduce the specific heat and enthalpy of polypropylene but the effect is not very great (Figure 13.11). If figures are not available for reinforced grades, it would be reasonable to use data for base grades which would then provide a small safety factor.

13.1.3 Shrinkage and warping

Shrinkage and warping are complex consequences of melt processing. For semi-crystalline plastics such as polypropylene the situation is particularly complicated. Crystalline regions exhibit a greater shrinkage than the surrounding amorphous regions, so semi-crystalline materials typically have a greater and more variable degree of shrinkage than amorphous materials.

Plastics melts are compressible, particularly at the high pressures used in injection molding and extrusion. The fundamental property is the relationship between pressure, volume and temperature. Measurements describing this relationship for any material are known as PVT data, and are usually shown graphically in the form of a PVT plot. The plot for polypropylene (Figure 13.12) shows the now-familiar discontinuity or “knee” in the curve that corresponds to the region of crystalline fusion. PVT plots for amorphous materials by contrast reveal a simple change of slope at a point corresponding to the glass transition temperature.

The PVT curves make it clear that shrinkage occurring as a result of melt processing is not just a function of thermal expansion and contraction but is also related to the compressibility of the melt. In practice, this relationship is made complex because process conditions will determine the extent to which the melt is compressed. Furthermore, process conditions are unlikely to be uniform throughout the part. Polypropylene shrinkage

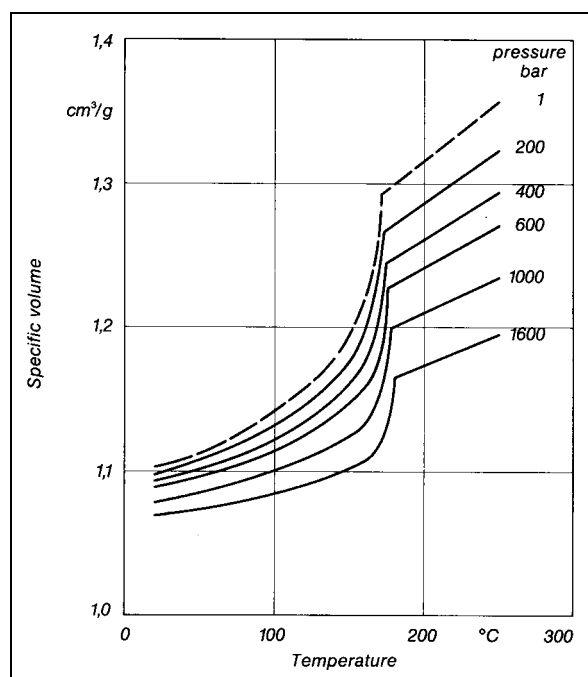


Figure 13.12 PVT plot for Hoechst Hostalen PPN 1060 polypropylene homopolymer, measured during heating up.

is related to the degree of crystallinity in the material and hence to the cooling rate. A greater degree of crystallinity leads to a higher rate of shrinkage and also to a greater differential between shrinkage in the flow direction and shrinkage measured transversely to flow. The differential effect is another consequence of the visco-elastic property of long-chain molecules. During flow, the molecules are aligned to a limited extent in the flow direction and are extended to a degree proportional to shear rate. On cooling, a partial recovery of this extension gives rise to a higher shrinkage value. The effect is more pronounced in materials with a wide distribution of molecular weight. It is the differential shrinkage that is responsible for warping, the name given to the distortion of an apparently correctly formed part during and after cooling.

A further difficulty is that shrinkage takes place over a period of time. In the case of an injection molding, the greater part of total shrinkage is evident virtually immediately after ejection from the mold but shrinkage will continue for more than 24 hours. During this time, further crystallization and relaxation of internal stresses result in small dimensional changes. Thereafter, further changes take place very slowly but the effect is dependent on temperature and will occur more rapidly if the part is exposed to elevated temperatures.

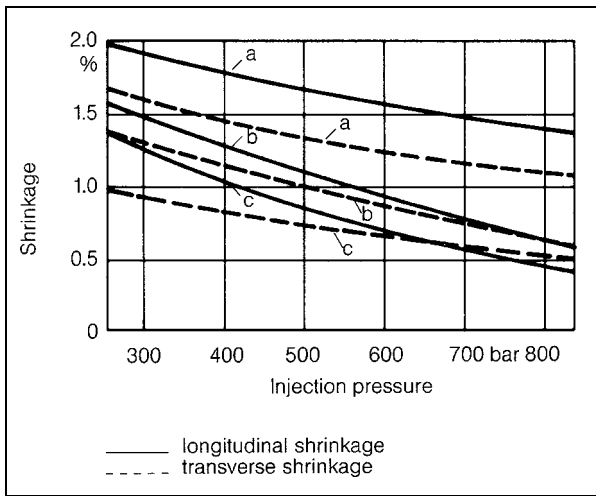


Figure 13.13 Shrinkage of some particulate-reinforced Hoechst polypropylenes. Key: a = non-reinforced base grade, b = Hoechst Hostacom M2 N01 (20% talc), c = Hoechst Hostacom M4 N01 (40% talc).

The sum of all these considerations means that it is impossible to state a simple and precise design figure for polypropylene shrinkage. Shrinkage can be minimized by using high viscosity, controlled rheology, or non-nucleated grade types. Warp can be limited by using materials with a narrow

Table 13.7 Approximate shrinkage range of polypropylene compared with other thermoplastics.

Polymer	Shrinkage (%)	Shrinkage (mm/mm)	Range (%)
SAN	0.4–0.6	0.004–0.006	0.2
PPO	0.5–0.7	0.005–0.007	0.2
PES	0.6–0.8	0.006–0.008	0.2
Polycarbonate	0.6–0.8	0.006–0.008	0.2
ABS	0.4–0.7	0.004–0.007	0.3
Polystyrene	0.4–0.7	0.004–0.007	0.3
Polyamide 11	0.3–0.7	0.003–0.007	0.4
PVC-U	0.4–0.8	0.004–0.008	0.4
PET	1.6–2.0	0.016–0.020	0.4
PMMA	0.3–0.8	0.003–0.008	0.5
Polyamide 6	0.2–1.2	0.002–0.012	1.0
Polyamide 12	1.0–2.0	0.010–0.020	1.0
Acetal	1.5–2.5	0.015–0.025	1.0
Polyamide 6/10	0.8–2.0	0.008–0.020	1.2
Polyamide 6/6	0.8–2.0	0.008–0.020	1.2
PBT	1.0–2.2	0.010–0.022	1.2
Polypropylene	1.2–2.5	0.012–0.025	1.3
HD polyethylene	1.5–3.0	0.015–0.030	1.5
LD polyethylene	1.0–3.0	0.010–0.030	2.0

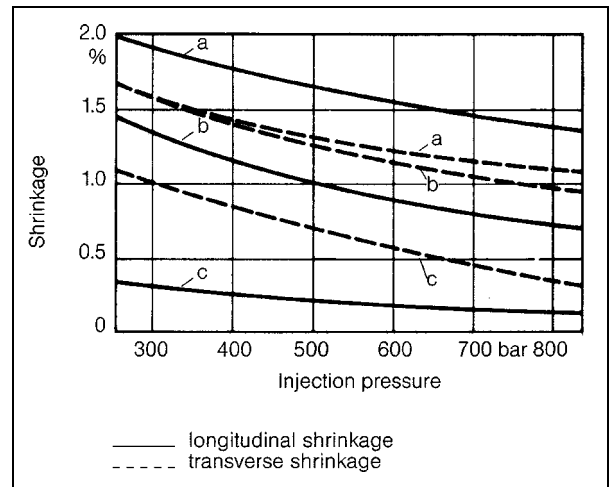


Figure 13.14 Shrinkage of fiber-reinforced polypropylenes. a) non-reinforced hose grade, b) 20% glass fiber, c) 30% glass fiber.

molecular weight distribution, particularly the controlled rheology types. Although it is a volumetric phenomenon, shrinkage is usually expressed as a linear quantity either as a percentage or as a linear ratio (mm per mm for example) (Table 13.7).

The effect of fillers and reinforcements on shrinkage depends largely on the physical form of the additive. Particulate fillers such as talc or glass beads tend to counteract the effect of molecular orientation and so not only reduce shrinkage, but also reduce shrinkage differentials and hence the tendency to warp (Figure 13.13).

Fibrous reinforcements also reduce shrinkage but because during flow the fibers become partially oriented, the reduction is much greater in the flow direction than in the transverse direction (Figure 13.14). This results in an increase in shrinkage differentials, although the increased tendency to warp is opposed to an extent by the greater stiffness of the reinforced material. In complex moldings, the varying flow patterns make it very difficult to anticipate shrinkage correctly by any means other than computer analysis. Even then, it is wise to design the product assembly to be tolerant of a degree of distortion and inaccuracy.

13.2 Pre-processing

Before any thermoplastic is processed into semi-finished or end products, and irrespective of the process to be adopted, there are a number of prior considerations to be taken into account. For polypropylene, the principal questions are those concerning drying (13.2.1), coloring (13.2.2), and health and safety precautions (13.2.3).

13.2.1 Drying

Polypropylene has a very low tendency to absorb water and will not normally require drying before processing. If any moisture is present, it will be as water condensed or adsorbed on the polypropylene surface. This can occur, for example, if polypropylene is moved from a relatively cool store to a warm and humid environment in the processing shop. Because the effect is purely a surface one, the moisture can be easily removed by conventional dryers but of course it is better to avoid the problem by attending to the storage conditions.

A simple hopper dryer will usually be sufficient to remove surface moisture from polypropylene granules. However, if the material is in the form of powder, the problem will be more severe, simply because of the greatly increased surface area available for adsorption. Powdered materials constitute an explosion hazard and should not be dried in conventional equipment intended for granules. Instead, the problem should be circumvented by storing producer-dried powders in sealed containers at equable temperatures. Certain carbon black or flame retardant grades of polypropylene have a somewhat increased tendency to attract moisture if stored for long periods in a damp atmosphere. In this case, drying should be performed at 105°C to 120°C for 1 to 3 hours. This treatment can also be applied to all polypropylene grades should hopper drying prove inadequate or be unavailable.

13.2.2 Coloring

Polypropylene is an essentially colorless material, ranging from milky white to near transparent depending on form and type. This characteristic means that it is possible to color the material to almost any desired shade by the inclusion of suitable dyes or pigments. The quality of the end result depends crucially on the even and thorough dispersion of the colorant throughout the polypropylene melt, and processors have a variety of means at their disposal for achieving this. Coloring operations can be broadly divided into those that are coincidental with the forming process (in-process coloring) and those that precede it (pre-process coloring).

Pre-process coloring (13.2.2.1) involves a separate coloring operation that takes place before the primary forming process. The method gives very good results but is relatively costly and adds to the heat history of the material. In-process coloring

methods are, as the name implies, carried out during and as an integral part of the primary forming process. These processes — injection molding, blow molding, extrusion — involve the use of an extruder screw as a melt plasticizer, and it is this that is pressed into service for the additional duty of dispersing a colorant additive throughout the melt. The process screws are not designed expressly for this duty and cannot be optimized for it. Instead, the machine designer has to compromise to produce a screw and barrel that will work well enough with a range of polymers, while providing a reasonable balance between the conflicting requirements of throughput, heat transfer, mixing, pressure, and cost. Process conditions too, must be a compromise between what is best for dispersion and what is best for the physical product.

Consequently, the principal worry with in-process coloring is how to achieve widespread, uniform, and repeatable dispersion of color additives. Mixing can be improved by the addition of simple static mixers such as screen packs or flow-divider nozzles, but at the cost of greater process pressure drops and perhaps reduced throughput. On the plus side, no additional heat history is imparted to the material, and the equipment, energy, and time is effectively free. The processor also has no need to hold large inventories of bulk colored material, and can respond rapidly to changing needs and specifications. The three common methods of in-process coloring are color concentrate (13.2.2.2), liquid color (13.2.2.3), and dry color (13.2.2.4).

13.2.2.1 Color-compounded material

Color-compounded polypropylene comes to the processor already colored in standard or custom colors. These materials are produced either by the polypropylene manufacturer or more commonly by a specialist compounder. The color is added in a melt process, generally a continuous process using an extruder or a screw-based compounder. Batch wise processes can also be performed with internal or roll mixers but are less convenient and uniform for thermoplastics. The color compounding process concludes with a pelleting operation that results in colored granules ready for use in injection molding, extrusion, and other forming processes.

The compounding equipment can be optimized for mixing, so the colorants are uniformly and widely dispersed throughout the material. Together with the availability of specialist color formulation and color measuring equipment, this

gives consistent and high quality results but there are a number of disadvantages. Polypropylene is prone to oxidation at melt temperatures and must be stabilized to counteract this. By imposing an extra melt operation, the color compounding process adds to the thermal strain or as it is often known, the heat history of the material. The additional operation also adds an extra cost which is partially offset by the efficiency gains of a dedicated business. Standard color ranges are necessarily limited, and the minimum order quantity for custom colors may be high.

Color-compounded materials are used by the processor in exactly the same way as natural grades of polypropylene. Color dispersion is already complete, so process conditions and equipment need take no account of this consideration. The color shade of the finished article can be taken for granted, provided quality checks are performed on the incoming compound. Minor process parameter adjustments may be necessary when changing from natural to color-compounded material but this is just a function of the minor rheological and thermal effects of the color additive on the polypropylene matrix.

13.2.2.2 Color concentrate or masterbatch

Color concentrate combines some of the advantages of pre-process and in-process coloring. The color concentrate is a thermoplastic compounded in the pre-process manner with a very high loading of colorant. It is then added in a minor proportion to natural (uncolored) polypropylene, and the process plasticizing screw has the task of mixing and distributing the colored polymer proportion throughout the mass of natural material. This requirement is relatively unexacting because the primary task of dispersion has already been performed during manufacture of the color concentrate. Consequently, there should be no chance of color agglomerates forming, even if the process screw is a relatively inefficient mixer.

The degree of dilution, or in other words the proportion of concentrate added to the polypropylene to be colored, is known as the let-down ratio. The concentrate manufacturer will aim to get the ratio as large as possible, but it is limited by the mixing efficiency of the conversion machinery and by the practicalities of concentrate compounding.

Color concentrate is now the most widely used method of coloring polypropylene. The processor requires only simple metering equipment to con-

trol the let-down ratio, and the added heat history is negligible. On the downside, the carrier polymer used in production of the color concentrate may have a minor effect on processing and on the properties of the finished part. This is because the carrier for a polypropylene color concentrate is unlikely to have exactly the same characteristics as the grade being colored. Indeed, the carrier may well be of polyethylene rather than polypropylene. These differences arise from the economic and logistical need to produce a near-universal color concentrate. The effects are usually insignificant provided the let-down ratio remains large.

13.2.2.3 Liquid color

Liquid color has not achieved the popularity among processors that it once promised, perhaps because of the need to retro-fit metering pump equipment to the process machinery. The method is probably best suited to long runs of a particular color. The colorants are dispersed in a liquid carrier base to form an ink-like material which is pumped into the entry of the plasticizing screw at a metered rate proportional to the throughput of polymer. Both the initial dispersion of colorants in the carrier, and the secondary mixing with the natural polypropylene are relatively easy because of the low viscosity of the liquid color. This also makes it possible to use very high let-down ratios that help to minimize the effect of the carrier on the processing and finished properties of the product. Cleaning, color changes, and spills are more troublesome to deal with than is the case for color concentrates.

13.2.2.4 Dry color

Once the most popular method with injection molders, dry color has now been displaced by color concentrates. The method appears simple but is the one most likely to result in inadequate color dispersion and shift-to-shift irregularities. The color additive in the form of a powder is initially distributed in the polymer solid phase rather than the melt phase. This is done by mixing dry color with polypropylene granules in mechanical blending equipment such as tumble or ribbon blenders. The aim is to coat the granules evenly with color particles, and additives may be used to promote the distribution and adhesion of the particles.

Among the many disadvantages are the need to handle hazardous dusty materials, the high survival rate of unbroken color agglomerates, the dif-

ficulty of cleaning the equipment, and the likelihood of inadequate color quality assurance and control. The color-coated granules are subsequently processed in conventional machinery, where the plasticizing screw has the exacting duty of wetting the color particles with the plastics melt and then dispersing them evenly throughout the mass. The task is at the outer limit of the mixing capability of melt process plasticizing systems and results rarely match the quality and uniformity of those obtained by the other coloring methods.

13.2.3 Safety precautions

Polypropylene is an intrinsically safe and non-toxic material, and when correctly processed no harmful vapors should be formed. Nevertheless, it is good practice to ventilate process workplaces. This is particularly true when processing flame retardant grades or when the material is exposed at high temperatures to the atmosphere, as it is for example in film extrusion.

The material is combustible at 345°C to 360°C and forms molten burning droplets that may spread the fire, so polypropylene processing plants should be equipped with fire precautions to the appropriate local standard. Water, powder and CO₂ extinguishers can be used in the event of a fire, and a mask should be worn to prevent the inhala-

tion of combustion fumes. Burning polypropylene will stick to the skin and cause severe burns so protective clothing and particularly gloves are necessary when tackling a fire.

Polypropylene is normally supplied in the form of granules that do not present an explosion hazard. However, finely divided polypropylene in the form of dust or powder does, like many other materials, create a risk of explosion. Transportation and handling systems should be designed to minimize dust formation, and should be cleaned regularly to prevent dust accumulations. Powdered polypropylene should be subject to the precautions required for other flammable explosive dusts. The movement of granules during discharge from bulk containers is likely to generate static charges that may cause shocks and sparks, and may interfere with electronic equipment. Silos and bins should be earthed to prevent this.

Polypropylene producers supply materials safety data sheets (MSDS) that summarize the risks precautions to be observed when working with the material (Figure 13.15)

References for chapter 13:

1004, 1012, 1016, 1032, 1049, 1057, 1059, 1063, 1101, 1102, 1106, 1150, 1151, 1153, 1154, 1156, 1183, 1216, 1220

Figure 13.15 Typical materials safety data sheet for polypropylene.

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EXXON CHEMICALS -- ESCORENE POLYPROPYLENE
MATERIAL SAFETY DATA SHEET
FSC: 6850
NIIN: 00N018142
Manufacturer's CAGE: 29700
Part No. Indicator: A
Part Number/Trade Name: ESCORENE POLYPROPYLENE
=====
                                General Information
=====
Company's Name: EXXON CHEMICALS CO
Company's P. O. Box: 3272
Company's City: HOUSTON
Company's State: TX
Company's Country: US
Company's Zip Code: 77001
Company's Emerg Ph #: 713-656-3424;800-424-9300 (CHEMTREC)
Company's Info Ph #: 713-656-2443
Record No. For Safety Entry: 001
Tot Safety Entries This Stk#: 001
Status: SMJ

```

Date MSDS Prepared: 24FEB89
Safety Data Review Date: 18DEC91
MSDS Serial Number: BLXSP
Hazard Characteristic Code: N1
=====

Ingredients/Identity Information
=====

Proprietary: NO
Ingredient: PROPENE POLYMERS; (POLYPROPYLENE). PEL:15 MG/M3 TDUST;5 MG/M3 RDUST. PEL & TLV AS PARTICULATES NOT OTHERWISE REGULATED.
Ingredient Sequence Number: 01
NIOSH (RTECS) Number: UD1842000
CAS Number: 9003-07-4
OSHA PEL: SEE INGRED NAME
ACGIH TLV: 10 MG/M3 TDUST
=====

Physical/Chemical Characteristics
=====

Appearance And Odor: CLEAR TO OPAQUE, WHITE (OR COLORED) SOLID PELLETS OR GRANULES.
Boiling Point: N/A
Melting Point: >225F,>107C
Vapor Pressure (MM Hg/70 F): NEGLIGIBLE
Specific Gravity: 0.88
Evaporation Rate And Ref: NOT APPLICABLE
Solubility In Water: INSOLUBLE
=====

Fire and Explosion Hazard Data
=====

Flash Point: >600F,>316C
Lower Explosive Limit: N/A
Upper Explosive Limit: N/A
Extinguishing Media: WATER SPRAY.
Special Fire Fighting Proc: USE H&2O SPRAY TO COOL FIRE EXPOS SURF & TO PROT PERS. ISOLATE FUEL SUPPLY FROM FIRE. WEAR NIOSH/MSHA APPRVD SCBA & FULL PROT EQUIP (FP N).
Unusual Fire And Expl Hazrds: SOLID MATL MAY BURN @/ABOVE FLASHPOINT & AIRBORNE DUST MAY EXPLODE IF IGNITED. TOX GASES WILL FORM UPON COMBUSTION. STATIC DISCHARGE MATL CAN ACCUM (SUPP DATA)
=====

Reactivity Data
=====

Stability: YES
Cond To Avoid (Stability): TEMPS OVER 480F MAY CAUSE RESIN DEGRADATION.
Materials To Avoid: NONE SPECIFIED BY MANUFACTURER.
Hazardous Decomp Products: OXYGEN-LEAN CONDITIONS MAY PRODUCE CARBON MONOXIDE & IRRITATING SMOKE.
Hazardous Poly Occur: NO
Conditions To Avoid (Poly): NOT RELEVANT.

=====

Health Hazard Data

=====

LD50-LC50 Mixture: NONE SPECIFIED BY MANUFACTURER.

Route Of Entry - Inhalation: YES

Route Of Entry - Skin: NO

Route Of Entry - Ingestion: NO

Health Haz Acute And Chronic: EYE:PARTICULATES MAY SCRATCH SURF/CAUSE MECH IRRIT. SKIN:EXPOS TO HOT MATL MAY CAUSE THERMAL BURNS. NEGLIGIBLE HAZARD @ AMBIENT TEMP. INHAL:NEGLIGIBLE HAZARD @ AMBIENT TEMP. VAPS AND/OR AEROSOLS WHICH MAY BE FORMED @ ELEVATED TEMPS MAY BE IRRIT TO EYES & RESP TRACT. INGEST:MINIMAL TOXICITY.

Carcinogenicity - NTP: NO

Carcinogenicity - IARC: NO

Carcinogenicity - OSHA: NO

Explanation Carcinogenicity: NOT RELEVANT.

Signs/Symptoms Of Overexp: SEE HEALTH HAZARDS.

Med Cond Aggravated By Exp: NONE SPECIFIED BY MANUFACTURER.

Emergency/First Aid Proc: EYE:IMMED FLUSH W/POTABLE WATER FOR MINIMUM OF 15 MIN, SEEK ASSIST FROM MD (FP N). SKIN:FOR HOT PROD, IMMED IMMERSE IN/ FLUSH AFFECTED AREA W/LG AMTS OF COLD H2O TO DISSIPATE HEAT. COVER W/CLEAN COTTON SHEET/GAUZE & GET MD IMMED. NO ATTEMPT SHOULD BE MADE TO REMOVE MATL FROM SKIN/TO REMOVE CONTAM CLTHG, AS DAMAGED FLESH CAN EASILY BE TORN. INHAL:IMMED REMOVE AFFECTED VICTIM FROM EXPOS. (SUPP DATA

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Precautions for Safe Handling and Use

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Steps If Matl Released/Spill: RECOVER SPILLED MATERIAL & PLACE IN SUITABLE CONTAINERS FOR RECYCLE OR DISPOSAL.

Neutralizing Agent: NONE SPECIFIED BY MANUFACTURER.

Waste Disposal Method: CONSULT EXPERT ON DISPOSAL OF RECOVERED MATL & DISPOSE OF I/A/W FEDERAL, STATE & LOCAL REGULATIONS.

Precautions-Handling/Storing: NONE SPECIFIED BY MANUFACTURER.

Other Precautions: NONE SPECIFIED BY MANUFACTURER.

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Control Measures

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Respiratory Protection: WHERE CONCENTRATIONS IN AIR MAY EXCEED LIMIT GIVEN, WORK PRACTICE OR OTHER MEANS OF EXPOSURE REDUCTION ARE NOT ADEQUATE. NIOSH/MSHA APPROVED RESPIRATORS MAY BE NECESSARY TO PREVENT OVEREXPOSURE BY INHALATION.

Ventilation: LOC EXHAUST VENT OF PROCESS EQUIP MAY BE NEEDED TO CONTROL PARTICULATE EXPOSURES TO BELOW RECOMMENDED EXPOSURE LIMIT.

Protective Gloves: THERMAL RESISTANT GLOVES.

Eye Protection: CHEM WORK GOG & FULL LENGTH FSHLD(FP N).

Other Protective Equipment: ARM PROTECTION.

Work Hygienic Practices: NONE SPECIFIED BY MANUFACTURER.

Suppl. Safety & Health Data: EXPLO HAZ:STATIC CHARGES WHICH CAN CAUSE INCENDIARY ELEC DISCHARGE. FIRST AID PROC:ADMIN ARTF RESP IF BRTHG IS STOPPED. KEEP @ REST. CALL FOR PROMPT MED ATTN. INGEST:CALL MD IMMED (FP N)


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                                Transportation Data
=====
Trans Data Review Date:    92065
DOT PSN Code: ZZZ
DOT Proper Shipping Name: NOT REGULATED BY THIS MODE OF TRANSPORTATION
IMO PSN Code: ZZZ
IMO Proper Shipping Name: NOT REGULATED FOR THIS MODE OF TRANSPORTATION
IATA PSN Code: ZZZ
IATA Proper Shipping Name: NOT REGULATED BY THIS MODE OF TRANSPORTATION
AFI PSN Code: ZZZ
AFI Prop. Shipping Name: NOT REGULATED BY THIS MODE OF TRANSPORTATION
Additional Trans Data: NOT REGULATED FOR TRANSPORTATION
=====
                                Disposal Data
=====
                                Label Data
=====
Label Required: YES
Technical Review Date: 18DEC91
Label Date: 18DEC91
Label Status: G
Common Name: ESCORENE POLYPROPYLENE
Chronic Hazard: NO
Signal Word: CAUTION!
Acute Health Hazard-Slight: X
Contact Hazard-Slight: X
Fire Hazard-Slight: X
Reactivity Hazard-None: X
Special Hazard Precautions: COMBUSTIBLE. ACUTE: PARTICULATES MAY SCRATCH
SURFACE/CAUSE MECHANICAL IRRITATION TO EYES. VAPORS AND/OR AEROSOLS WHICH
MAY BE FORMED AT ELEVATED TEMPERATURES MAY BE IRRITATING TO EYES AND
RESPIRATORY TRACT. MINIMAL TOXICITY IF SWALLOWED. CHRONIC: NONE LISTED BY
MANUFACTURER.
Protect Eye: Y
Protect Skin: Y
Protect Respiratory: Y
Label Name: EXXON CHEMICALS CO
Label P.O. Box: 3272
Label City: HOUSTON
Label State: TX
Label Zip Code: 77001
Label Country: US
Label Emergency Number: 713-656-3424;800-424-9300(CHEMTREC)
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14 Injection molding

Introduction

Almost a third of polypropylene consumption is processed by means of injection molding. The process produces a complex finished part in a single rapid and automatic operation. It is this that distinguishes plastics injection molding from most other manufacturing processes, although there are parallels with metal casting, and particularly with die-casting. Generally speaking, it would need a whole series of forming, joining, and finishing operations to replicate an injection molded article in other materials using different manufacturing methods. It is this point alone that makes injection molding economically viable. Injection molding machines and molds are very costly due to the high pressures needed to inject thermoplastics and the complexity of the necessary process controls. It is only the ability to produce a completely finished part at high speed that balances the equation and makes the injection molded article highly cost effective.

Injection molded polypropylene parts are a familiar part of everyday life. In the home, they can be found in household appliances, kitchen equipment, in containers and caps, toys, and in the frames and shell of chairs. On the road, they are a key feature of the modern automobile in the form of fenders, fascias, trims, wheel well liners, and housings. In healthcare, injection molded polypropylene is the material of choice for disposable syringes. At work, they can be found in office equipment, crates and cases, and paint pots. Other familiar uses include food containers, video cassette boxes, and luggage.

14.1 The process

The principle of injection molding is very simple. The plastics material is heated until it becomes a viscous melt. It is then forced into a closed mold that defines the shape of the article to be produced. There the material is cooled until it reverts to a solid, then the mold is opened and the finished part is extracted. Although the principle may be simple, the practice of injection molding is anything but simple. This is a consequence of the complex behavior of plastics melts and the ability of the process to encompass complicated products.

The essential mechanisms of injection molding are heat transfer and pressure flow. The essential equipment is an injection molding machine, sometimes known as a press, and a mold which may also be referred to as a tool or sometimes a die. The product of the process is a molding which confusingly and inaccurately is sometimes called a mold.

14.2 Injection molding machinery

There are many varieties of injection molding machines, but they all perform the same essential functions. These are melting or plasticizing the plastics material, injecting it into the mold, holding the mold closed, and cooling the injected material. It is convenient to think of an injection molding machine as consisting of two units. The plasticizing and injection requirements are combined in the injection unit while the mold handling is performed by the clamp unit. The two units are mounted on a common machine base and are integrated by power and control systems. The convention is that the injection unit shall be on the right of the operator, with the clamp unit on the left (Figure 14.1).

14.2.1 Clamp unit

The function of the clamp unit is to open and close the mold halves and particularly to hold the mold closed during injection of the plastics melt. High injection pressures are necessary, due to the high viscosity of plastics melts, so the force needed to hold the mold closed is very great. The melt pressure inside the mold is exerted over the entire area of cavities and feed systems at the mold parting line. The significant figure is the extent of this area

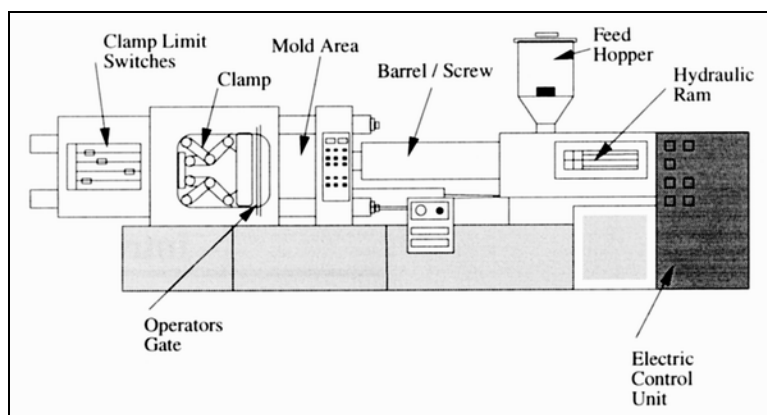


Figure 14.1 Typical injection molding machine.

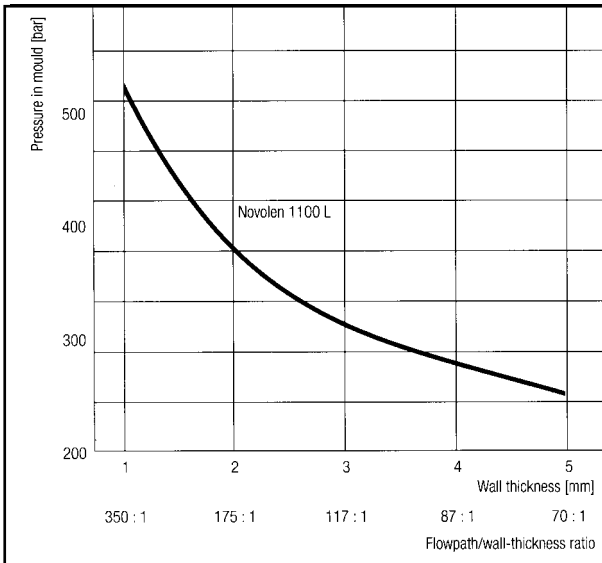


Figure 14.2 Average mold pressure as a function of wall thickness for BASF Novolen1100L polypropylene homopolymer at 230°C.

when projected on to a plane perpendicular to the opening axis of the clamp system. This is known as the projected area of the mold. The clamp force needed to hold the mold shut during injection is a function of the injection pressure and the projected area, but this is not a simple function. The injection pressure varies throughout the cavities and feed systems and is also a complex function of process parameters such as melt and mold temperature, and injection rate. The cavity pressure is also a function of part thickness (Figure 14.2) which is completely independent of projected area, so attempts to determine clamp force on the basis of projected area are sure to be inaccurate. The means that the old rule-of-thumb method of allotting x units of clamp force per unit of projected area should be seen as a last resort. It is one that is likely to lead to under utilization of machines due the need for a large safety factor to cover the deficiencies of the method. The rule-of-thumb clamp figure for polypropylene is 2

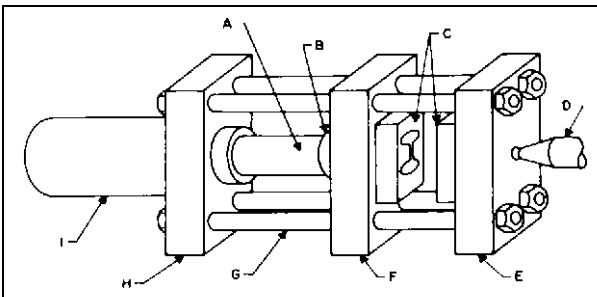


Figure 14.3 Typical direct hydraulic clamp unit. A-Actuating plunger, B-Removable spacer, C-Mold, D-Injection nozzle, E-Fixed platen, F-Movable platen, G-Tie bar, H-Cylinder base plate, I-Clamping cylinder.

to 4 tons per square inch of projected area. More reliable methods of determining clamp force are discussed in section 14.4.2.

Clamp units range up to 3,000 tonnes closing force and more. The force requirements ensure that the clamp unit must be engineered very robustly, but this conflicts with the need to open and close the mold rapidly to minimize production time. A variety of clamp mechanisms has evolved in the search for a suitable compromise. The two most common types are the direct hydraulic clamp (Figure 14.3) and the toggle clamp (Figure 14.4). Other variants include hybrid toggle/hydraulic types, lock-and-block systems, and electro-mechanical systems.

Whatever the variations, the clamp unit always features a stationary or fixed platen and a moving platen on which the mold halves are bolted or otherwise attached. The fixed platen is mounted rigidly on the machine base and is positioned adjacent to the nozzle of the injection unit. The injection half of the mold is attached to the fixed platen while the moving platen carries the ejection half of the mold. These terms may in the case of some sophisticated molds cease to be literally true, and the expressions fixed and moving mold halves are often used instead.

The clamp also includes a tailstock platen or equivalent unit that the pressure means reacts against in order to clamp the mold halves together between the moving and fixed platens. For this purpose, the fixed and tailstock platens are united by tiebars (tie rods) that also serve as guides for the moving platen. The tiebars are stretched elastically when the clamp unit locks the mold shut under pressure. The tiebars limit access to the mold area and impede mold changing, and it is to overcome this that tiebarless machines have been intensively developed in recent years. The tiebarless machine uses the same clamp concepts but employs a greatly strengthened machine base to tie the fixed and tail-

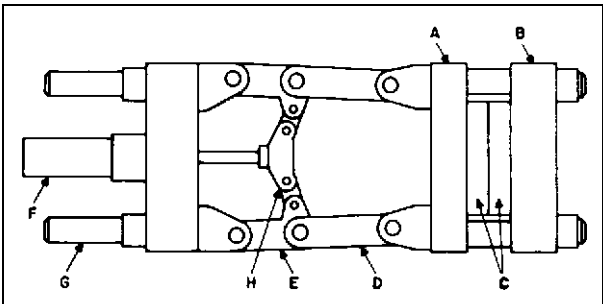


Figure 14.4 Typical toggle clamp unit. A-Movable platen, B-Fixed platen, C-Mold, D-Front link, E-Rear link, F-Actuating Cylinder, G-Tie bar, H-, I-Crosshead link.

stock platens together. The result is a completely unencumbered mold area with free access for automation, ancillaries, and mold changing operations. Under clamp pressure, the machine frame and platens flex elastically. Tiebarless machines use a variety of means to counteract this tendency and keep the platens parallel. However, the effect limits the clamp force that can be designed into tiebarless machines although the figure is gradually being pushed upwards. Currently the limit is about 400 tonnes.

Another recent development, particularly in large injection molding machines, is a move towards two-platen clamp systems. These systems do away with the tailstock platen and use a variety of mechanisms to lock the tiebars to the moving platen in the closed position. The advantage of a two-platen clamp is a considerable saving of up to 35% in floor space.

Clamp units are rated according to the maximum closing force they can apply to the mold. The figure may be expressed as kiloNewtons (kN), metric tonnes (tonne) or US tons (ton) (Table 14.1).

14.2.2 Injection unit

The function of the injection unit is to heat the plastics material to a uniform and homogeneous melt and to inject it into the mold under controlled conditions of pressure and flow rate. Given the low thermal conductivity, high specific heat, and high melt viscosity of thermoplastics, these are exacting tasks. Once again, many variants have been devised to solve the difficult problems involved. The variants can be grouped roughly into four principal injection unit concepts:

- single-stage ram or plunger
- two-stage ram
- single-stage screw
- two-stage screw/ram

The single-stage ram unit is inefficient in heating, mixing and pressure transmission and is largely obsolete although the form survives in very small machines and some specialized equipment. It has the merit of simplicity and low cost. The two-stage ram is also all but obsolete. It was an attempt to improve on the single-stage ram by

Table 14.1 Clamp force conversion table

Nominal value (tonne)	Equiv. Value (ton)	Equiv. Value (kN)	Nominal Value (ton)	Equiv. Value (tonne)	Equiv. Value (kN)	Nominal value (kN)	Equiv. Value (tonne)	Equiv. Value (ton)
25	27.6	245.2	25	22.7	222.4	250	25.5	28.1
50	55.1	490.3	50	45.4	444.8	500	51.0	56.2
75	82.7	735.5	75	68.0	667.2	750	76.5	84.3
100	110.2	980.7	100	90.7	889.6	1000	102.0	112.4
150	165.3	1471.0	150	136.1	1334.5	1500	153.0	168.6
200	220.5	1961.3	200	181.4	1779.3	2000	203.9	224.8
250	275.6	2451.7	250	226.8	2224.1	2500	254.9	281.0
300	330.7	2942.0	300	272.2	2668.9	3000	305.9	337.2
350	385.8	3432.3	350	317.5	3113.8	3500	356.9	393.4
400	440.9	3922.7	400	362.9	3558.6	4000	407.9	449.6
450	496.0	4413.0	450	408.2	4003.4	4500	458.9	505.8
500	551.2	4903.3	500	453.6	4448.2	5000	509.9	562.0
600	661.4	5884.0	600	544.3	5337.9	6000	611.8	674.4
700	771.6	6864.7	700	635.0	6227.5	7000	713.8	786.8
800	881.8	7845.3	800	725.7	7117.2	8000	815.8	899.2
1000	1102.3	9806.7	1000	907.2	8896.4	10000	1019.7	1124.0
1500	1653.5	14710.0	1500	1360.8	13344.7	15000	1529.6	1686.1
2000	2204.6	19613.3	2000	1814.4	17792.9	20000	2039.4	2248.1
2500	2755.8	24516.6	2500	2268.0	22241.1	25000	2549.3	2810.1
3000	3306.9	29420.0	3000	2721.6	26689.3	30000	3059.2	3372.1

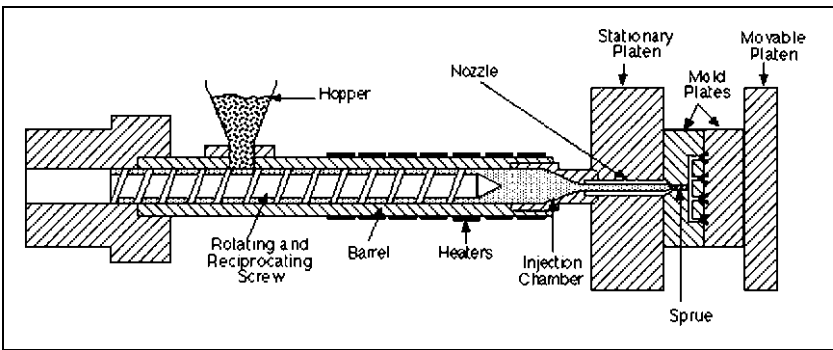


Figure 14.5 Typical reciprocating screw injection unit. [1221]

separating the functions of heating and pressure flow, but the ram remains an inefficient mixer and heater. The two-stage screw/ram unit also separates the functions of heat and flow, using a screw for heating and mixing, and a ram for injection. Both are relatively efficient devices for their respective duties so the concept is attractive. However, the unit cost is higher, and it is difficult to devise an ideal melt flow path between the stages. The single-stage screw concept is by far the dominant form. A screw capable of both rotational and axial movement combines heating and mixing with the function of injection. For this reason, the form is frequently referred to as a reciprocating screw injection unit (Figure 14.5).

The extruder-like screw operates within a heated barrel and has axial zones that are concerned successively with feeding, melting, and metering the plastics material. Many different screw forms have been designed in the search for the best compromise between plasticizing and throughput, particularly in recent years when CNC machining has made it possible to cut shapes that were previously impractical. The design process has been accelerated by extrusion simulation software that makes it possible to predict how a screw design will perform. Ideally, the screw should be optimized for use with a particular polymer, but this can only happen if it is known that the injection molding machine will be dedicated throughout its life to a narrow range of uses. Instead, virtually all injection molding machines are supplied with a screw that is designed as a compromise between the requirements for the majority of thermoplastics. This is known as a general-purpose screw. It is usual for a machine to be offered with additional

screw options for PVC and elastomers. Other options may include a so-called marbleizing screw for producing colored marble effects and a vented screw which includes a decompression zone and an associated exhaust port for the removal of water vapor or other volatiles. The practice is growing of offering two versions of the general-purpose screw for use with “commodity” or “engineering” plastics.

Most general-purpose screws take the form of a single constant-pitch flight that decreases in depth from the input or upstream end to the output or downstream end (Figure 14.6). The flight pitch is usually equal to the screw diameter, giving a helix angle of 17.8° . Flight depth is usually substantially constant in the feed and metering zones and decreases at a constant rate over the compression zone. The feed zone typically occupies half the screw length, with the compression and metering zones each making up a quarter of the length. The key parameters of such a screw are the ratio of length to diameter (the L/D ratio), and the compression ratio. The L/D ratio affects mixing and melt uniformity, higher values giving better results. An L/D ratio of 20:1 is regarded as a minimum for injection molding. Screws as long as 28:1 are offered by some manufacturers. The compression ratio has a bearing on mixing and shear heating. Typical values range from 2:1 to 3:1 or greater. It is this parameter that varies between “commodity” and “engineering” general-purpose screws. The terms are inexact and the real difference is between semi-crystalline and amorphous polymers. On heating to melt temperature, semi-crystalline materials undergo a greater volume increase than amorphous materials and so require a lower compression ratio.

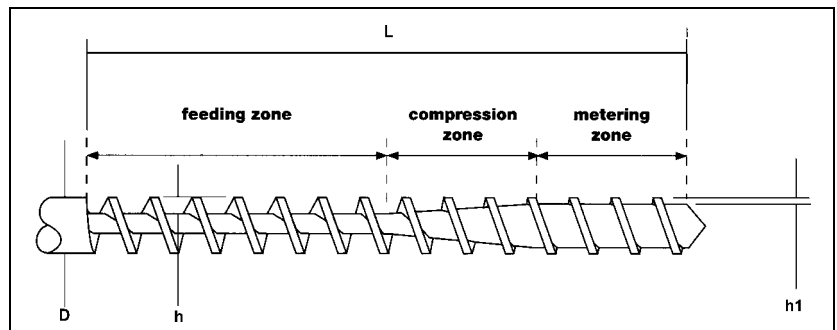


Figure 14.6 Features of a typical injection screw. Key: L = screw length, D = diameter, h = initial flight depth, h_1 = final flight depth, L/D = Length/diameter ratio, h/h_1 = Compression ratio

Preferred screws for use with polypropylene should have an L/D ratio in the range 20:1 to 25:1, and a compression ratio of 2.3:1 to 2.8:1.

The basic sequence of events in the injection unit is:

- The screw rotates, so heating and melting the material which is conveyed along the screw flights to the downstream end of the screw. The barrel nozzle is closed by thermal or mechanical valve means or by the presence of a previously-made molding. The accumulating melt presses the still-rotating screw back against a controlled resistance (the back pressure) until sufficient melt has accumulated to make the next molding. At this point, screw rotation stops. This is the melt preparation phase.
- The barrel nozzle is opened and the screw performs the action of a ram by moving forward in the axial direction without rotating. This forces (injects) the melt that has accumulated ahead of the downstream end of the screw through the nozzle and into the mold. The

downstream end of the screw may be equipped with a valve arrangement to prevent melt flowing back down the screw flights. This is the mold filling or injection phase.

- After the mold is filled, screw pressure is maintained for short period to compensate for volumetric shrinkage of the cooling melt contained in the mold. This is the packing or holding phase.
- At the conclusion of the holding phase, and while the mold remains closed for the molding to cool to ejection temperature, the injection unit cycle recommences with the resumption of screw rotation and melt preparation.

Injection units are rated in terms of the maximum injection pressure and injection volume available. Injection pressure is the theoretical maximum available at the downstream end of the screw. This is a function of the screw diameter and the force acting on it. It should not be confused, as it often is, with the hydraulic line pressure acting on the injec-

Table 14.2 Injection pressure conversion table

Nominal value (psi)	Equiv. Value (bar)	Equiv. Value (MPa)	Nominal value (bar)	Equiv. Value (psi)	Equiv. Value (MPa)	Nominal value (MPa)	Equiv. Value (psi)	Equiv. Value (bar)
10000	689.5	68.9	600	8702.3	60.0	60	8702.3	600.0
11000	758.4	75.8	700	10152.7	70.0	70	10152.7	700.0
12000	827.4	82.7	800	11603.0	80.0	80	11603.0	800.0
13000	896.3	89.6	900	13053.4	90.0	90	13053.4	900.0
14000	965.3	96.5	950	13778.6	95.0	95	13778.6	950.0
15000	1034.2	103.4	1000	14503.8	100.0	100	14503.8	1000.0
16000	1103.2	110.3	1050	15229.0	105.0	105	15229.0	1050.0
17000	1172.1	117.2	1100	15954.2	110.0	110	15954.2	1100.0
18000	1241.1	124.1	1150	16679.4	115.0	115	16679.4	1150.0
19000	1310.0	131.0	1200	17404.6	120.0	120	17404.6	1200.0
20000	1379.0	137.9	1250	18129.8	125.0	125	18129.8	1250.0
21000	1447.9	144.8	1300	18854.9	130.0	130	18854.9	1300.0
22000	1516.8	151.7	1350	19580.1	135.0	135	19580.1	1350.0
23000	1585.8	158.6	1400	20305.3	140.0	140	20305.3	1400.0
24000	1654.7	165.5	1450	21030.5	145.0	145	21030.5	1450.0
25000	1723.7	172.4	1500	21755.7	150.0	150	21755.7	1500.0
26000	1792.6	179.3	1600	23206.1	160.0	160	23206.1	1600.0
27000	1861.6	186.2	1700	24656.5	170.0	170	24656.5	1700.0
28000	1930.5	193.1	1800	26106.8	180.0	180	26106.8	1800.0
29000	1999.5	199.9	1900	27557.2	190.0	190	27557.2	1900.0
30000	2068.4	206.8	2000	29007.6	200.0	200	29007.6	2000.0

tion cylinder that supplies the force to the screw. Nor should it be taken as the pressure available to fill the mold cavities. This is much less because of pressure losses in the nozzle and mold feed systems. Injection pressures are normally quoted in megaPascals (MPa), atmospheric pressures (bar), or pounds per square inch (psi) (Table 14.2).

The maximum injection volume or swept volume is the product of the screw diameter and its maximum retraction stroke during plasticizing. The value is expressed in cubic centimeters (cm³), cubic inches (in³), and sometimes as the weight in ounces (oz) or grams (gm) of plastic material that can be injected (Table 14.3). The weight rating is a less accurate measure and is relative to the density of the plastics material in question. Quoted injection weight or shot weight ratings are usually referenced

to GP polystyrene. The figure used to make the conversion should be the density in the melt state rather than in the solid state (Table 14.4).

In principle, the entire theoretical shot volume is available for injection. In practice, the volume is limited by the concept of residence time. This is the time that an element of plastics material takes to pass through the screw and barrel system. It is a function of cycle time and injection stroke. The significance of residence time rests on the fact that a plastics material may begin to degrade if exposed too long to process temperatures normally regarded as safe. Residence time itself is independent of material, but the sensitivity of materials to residence time varies and is at its greatest with materials such as PVC that are processed at a point close to the degradation temperature. Polypropyl-

Table 14.3 Shot volume conversion table

Nominal shot volume (cm ³)	Equiv. Volume (in ³)	Equiv. shot weight in GPPS (gm)	Equiv. Shot weight in GPPS (oz)	Nominal shot volume (in ³)	Equiv. Volume (cm ³)	Equiv. Shot weight in GPPS (gm)	Equiv shot weight in GPPS (oz)
25	1.5	22.0	0.8	2	32.8	28.8	1.0
50	3.1	44.0	1.6	3	49.2	43.3	1.5
75	4.6	66.0	2.3	4	65.5	57.7	2.0
100	6.1	88.0	3.1	5	81.9	72.1	2.5
125	7.6	110.0	3.9	6	98.3	86.5	3.1
150	9.2	132.0	4.7	7	114.7	100.9	3.6
175	10.7	154.0	5.4	8	131.1	115.4	4.1
200	12.2	176.0	6.2	9	147.5	129.8	4.6
250	15.3	220.0	7.8	10	163.9	144.2	5.1
300	18.3	264.0	9.3	20	327.7	288.4	10.2
350	21.4	308.0	10.9	30	491.6	432.6	15.3
400	24.4	352.0	12.4	40	655.5	576.8	20.3
450	27.5	396.0	14.0	50	819.4	721.0	25.4
500	30.5	440.0	15.5	60	983.2	865.2	30.5
750	45.8	660.0	23.3	70	1147.1	1009.4	35.6
1000	61.0	880.0	31.0	80	1311.0	1153.6	40.7
1500	91.5	1320.0	46.6	90	1474.8	1297.9	45.8
2000	122.0	1760.0	62.1	100	1638.7	1442.1	50.9
2500	152.6	2200.0	77.6	150	2458.1	2163.1	76.3
3000	183.1	2640.0	93.1	200	3277.4	2884.1	101.7
4000	244.1	3520.0	124.2	250	4096.8	3605.2	127.2
5000	305.1	4400.0	155.2	500	8193.5	7210.3	254.3
10000	610.2	8800.0	310.4	750	12290.3	10815.5	381.5
15000	915.4	13200.0	465.6	1000	16387.1	14420.6	508.7

Table 14.4 Shot weight conversion factors

Polymer	Multiply volume (cm ³) by this factor to obtain shot weight (gm)	Multiply volume (cm ³) by this factor to obtain shot weight (oz)	Multiply volume (in ³) by this factor to obtain shot weight (gm)	Multiply volume (in ³) by this factor to obtain shot weight (oz)
LD polyethylene	0.79	0.028	12.95	0.46
HD polyethylene	0.81	0.029	13.27	0.47
Polypropylene	0.85	0.030	13.93	0.49
Polystyrene	0.88	0.031	14.42	0.51
ABS	0.89	0.031	14.58	0.51
PPO	0.92	0.032	15.08	0.53
SAN	0.92	0.032	15.08	0.53
Polyamide 6/6	0.95	0.034	15.57	0.55
Polyamide 6/6	0.97	0.034	15.90	0.56
PMMA	1.01	0.036	16.55	0.58
Polycarbonate	1.01	0.036	16.55	0.58
PBT	1.12	0.040	18.35	0.65
PET	1.15	0.041	18.85	0.66
PVC-U	1.15	0.041	18.85	0.66
Acetal	1.22	0.043	19.99	0.71
PES	1.48	0.052	24.25	0.86

ene has a tendency to oxidize and is routinely protected by the inclusion of anti-oxidants in the polymer production process. It is consequently unwise to expose polypropylene to lengthy residence times in the injection unit. Small shots produced from big machines are likely to lead to trouble, especially if the cycle time is slow.

The chart (Figure 14.7) shows residence times for a range of cycle times. Injection strokes are expressed in terms of D , the screw diameter. If for example, we wish to limit residence time to 5 minutes, this means that the injection stroke should not be less than about $1D$ for a 50 second cycle, or not less than about $0.6D$ for a 30 second cycle. The maximum injection stroke for a typical injection molding screw is about $4D$, so the two figures equate to about 25% and 15% of maximum shot volume respectively. The preferred shot volume is in the range $1D$ to $3D$, or 25% to 75% of the maximum available.

Allowable residence times for polypropylene depend on the material temperature. At 280°C , observable degradation occurs at about five minutes exposure. At 250°C the material will tolerate a much longer exposure.

The European Committee of Machinery Manufacturers for the Plastics & Rubber Industries has

developed a standard classification for injection molding machines. This is known as the Euromap international size classification and it consists of two numbers in the format xxx/xxx. The first number indicates the clamp force in kiloNewtons (kN). The second number is an injection unit rating derived by multiplying the maximum injection pressure (bar) by the shot volume (cm³) and dividing by 1000. This figure is useful for classifying injection molding machines that are supplied, as most are, with a choice of screw diameters. The maximum injection force exerted by the machine on the screw remains constant because only the screw and barrel assembly is interchanged. This means that shot volume is proportional to screw diameter but the maximum injection pressure is inversely proportional. The Euromap injection unit rating is unaffected by screw diameter. In other words, it returns the same figure for each of the alternative screw and barrel assemblies for a particular machine and so simplifies the task of classification. This rating is not much help in specifying an injection molding machine; maximum shot volume and injection pressure figures are indispensable for that purpose.

The normal screw and barrel assembly is designed for a maximum injection pressure in the region of 1500 bar (21,800 psi). A low-pressure high-

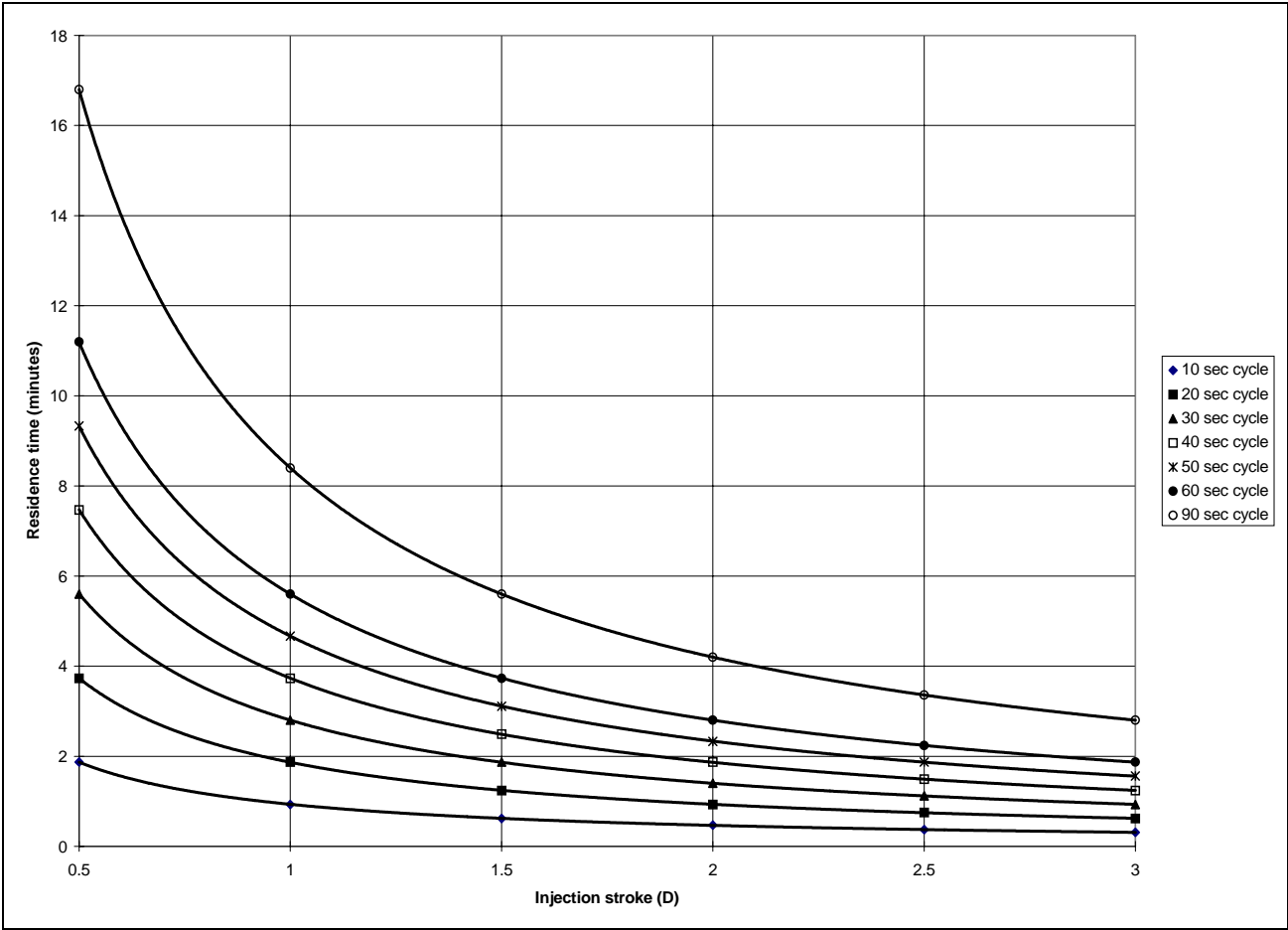


Figure 14.7 Material residence times. [1175]

volume alternative will operate in the region of 1200 bar (17,400 psi), while the high-pressure low-volume version will work at about 2000 bar (29,000 psi). Once again, these are the theoretical maxima at the downstream face of the screw. Thereafter, major pressure losses occur in forcing the plastics melt through the injection nozzle and thence through the mold feed system and cavities. These pressure losses cannot be quantified by simple rules. They are a function of the physical form of the flow path, the condition of the plastics melt, the rate of heat

exchange, the type of polymer, and the rate and pressure of injection. Specific figures can be calculated with adequate accuracy by computer simulations of the molding process. The example (Figure 14.8) shown holds good only for a specific combination of mold, material, machine, and process conditions, but it serves to illustrate the way in which theoretical maximum injection pressure is diminished before reaching the cavity. Pressure losses in the machine nozzle may account for a further cut of 200 psi to 1000 psi.

14.2.3 Power systems

Injection molding machines perform a wide range of mechanical movements with differing characteristics. Mold opening is a low-force high-speed movement, and mold closing a high-force low-speed movement. Plasticizing involves high torque and low rotational speed, while injection requires high force and medium speed. A source of motive power is needed to drive these movements. The modern injection molding machine is virtually always a self-contained unit incorporat-

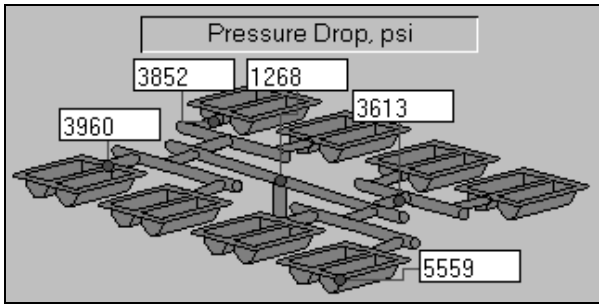


Figure 14.8 Example of computer-predicted pressure drops for a balanced 8-cavity mold using Pro-fax SB-823 polypropylene. [1175]

ing its own power source. Early machine frequency ran from a centralized source serving an entire shop or factory. In this respect, injection molding machines have undergone the same metamorphosis as machine tools.

Oil hydraulics has become firmly established as the drive system for the vast majority of injection molding machines and until recently was almost unchallenged as the power source. Put at its simplest, the injection molding machine contains a reservoir of hydraulic oil which is pumped by an electrically-driven pump at high pressure, typically at up to 2000 psi, to actuating cylinders and motors. High and low pressure linear movements are performed by hydraulic cylinders, and rotary movements for screw drive and other purposes are achieved by hydraulic motors. Hybrid machines, in which the screw is driven by electric motor while the linear movements remain hydraulically powered, are not uncommon.

In recent years, the supremacy of the hydraulic machine has been challenged by all-electric machines. These use new brushless servo motor technology to power the various machine movements. The capital cost of all-electric machines is higher than that of conventional machines but the energy consumption in production is much lower. This is because the electric motors run only on demand, and there are no losses due to energy conversion, pipelines, or throttling. The elimination of hydraulic oil makes the all-electric machine inherently cleaner, so these machines are attractive for sterile or clean room use. There is also evidence that all-electric machine movements can be resolved with a higher degree of precision and re-

Table 14.5 Some injection molding process control factors

Temperature	Time	Distance	Speed	Pressure or force	Profile
Melt	Hold changeover	Hold changeover	Screw rotation	Hold changeover	Injection pressure
Mold	Open	Fast open	Injection stroke	Injection	Injection speed
Nozzle	Carriage forward delay	Slow open	Carriage	Peak	Holding pressure
Barrel zones	Hold	Eject	Slow break	Holding	
Feed throat	Carriage back delay	Sprue break	Fast open	Back	
Pellets	Screw start delay	Suck back	Slow open	Nozzle hold-on	
	Cooling	Shot	Eject	Clamp close	
	Eject	Cushion		Clamp open	
	Cycle delay				

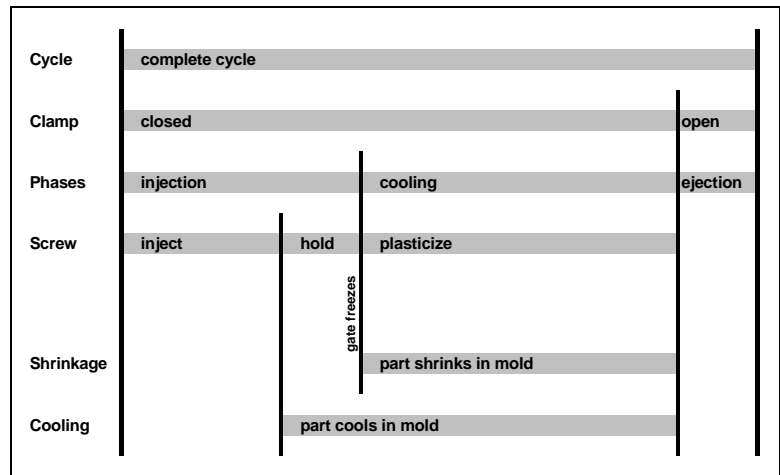


Figure 14.9 Principal elements of the injection molding cycle

peatability than hydraulic systems.

14.2.4 Control systems

The full sequence of operations and necessary options in a modern injection molding machine is very complex (Figure 14.9). So too, is the range of parameters and adjustments needed to control the process accurately and automatically (Table 14.5). Control is ultimately exercised by valves, regulators and switches but it is rare now for these to be under individual manual control. The norm now is electronic control of varying degrees of sophistication ranging from simple partial control by programmable logic controller up to full centralized computer control. It is usual for an injection molding machine to be offered with a choice of control options to suit a variety of end uses and budgets.

The precision and repeatability of injection molding machines has been much improved by the introduction of closed loop control to critical features like the injection screw sequence. The closed loop principle uses sensors to measure an impor-

tant parameter — speed, position, pressure — of the element to be controlled. The readings are processed by the control system which generates control signals to a servo valve that regulates the element. The process is often known as feedback. In effect, the system monitors itself to check whether it is performing as instructed and if not, it makes an adjustment based on the discrepancy.

14.3 Process conditions for polypropylene

Process conditions vary significantly from one molding project to another, depending not only on the configuration of the part but also on mold design, machine choice, and on the desired balance of properties and attributes in the finished part. Consequently, these process recommendations for polypropylene can be regarded as guidelines only. However, they will serve as a reliable starting point for the optimization of the injection molding process.

14.3.1 Filling

Like other thermoplastics, polypropylene can be

injection molded over a range of melt and mold temperatures. The table (Table 14.6) sets out the extremes that are practicable. In reality, most processing is performed in a narrower mid-range of values while the extremes are reserved for special circumstances. Polypropylene melt temperatures will normally be in the range 230°C to 260°C and mold temperatures in the region of 20°C to 40°C. Lower mold temperatures produced with a mold chiller may be used for fast-cycling parts with a high injection rate. A warmer mold improves surface gloss and weld lines. Mold temperatures above 60°C may be necessary when producing thick-walled parts; otherwise, premature surface freezing may result in the formation of internal voids.

The desired melt temperature is attained by gradually raising the temperature of the material as it travels along the screw. Heat is gained by conduction from the heated barrel and by shear work done on the material. It is usual to set the barrel heating zones in a gradually increasing temperature profile (Figure 14.10).

There are normally more than three zones of temperature control on the barrel. The table (Table

Table 14.6 Melt and mold temperature ranges for polypropylene compared with other thermoplastics.

Polymer	Melt temperature (°C)	Melt temperature (°F)	Mold temperature (°C)	Mold temperature (°F)
Polypropylene	200–300	390–570	20–90	70–195
ABS	200 –260	390–500	50–80	120–175
Acetal	180–320	355–445	60–120	140–250
HD polyethylene	200–300	390–570	10–60	50–140
LD polyethylene	160–270	320–520	20–60	70–140
PBT	230–280	445–535	40–80	105–175
PES	320–380	610–715	90–160	195–320
PET	260–300	500–570	130–150	265–300
PMMA	190–290	375–555	40–90	105–195
Polyamide 11	200–270	390–520	40–80	105–175
Polyamide 12	190–270	375–520	20–100	70–210
Polyamide 6	240–290	465–555	40–120	105–250
Polyamide 6/10	230–290	445–555	40–120	105–250
Polyamide 6/6	260–300	500–570	40–120	105 –250
Polycarbonate	270–380	520–715	80–120	175–250
Polystyrene	170–280	340–535	10–60	50–140
PPO	250–300	480–570	30–110	85–300
PVC-U	170–210	340–410	20–60	70–140
SAN	200–260	390–500	50–80	120–175

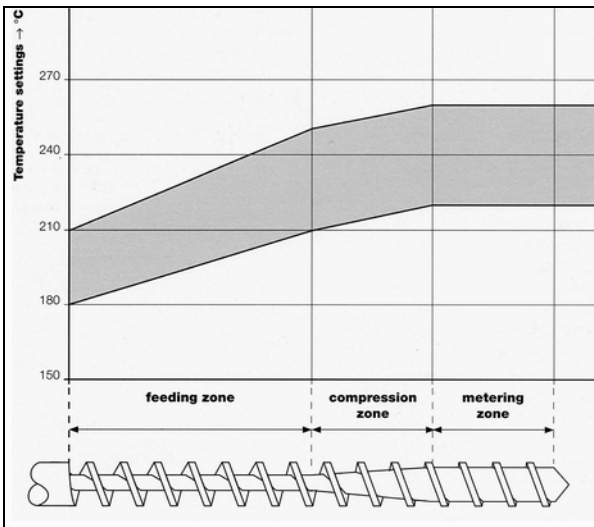


Figure 14.10 Temperature profile for DSM Statytec high crystallinity polypropylene.

14.7) shows a typical range of barrel temperature settings for polypropylene.

The shot volume can be up to 85% of the machine maximum shot volume. The minimum shot volume is determined by residence time in the way discussed earlier. If the injection proportion is being judged in terms of shot weight, remember to multiply the machine rating by a factor of 0.85 to convert it from the polystyrene standard to polypropylene.

Relatively high injection pressures are used, typically in the range 1200 bar (17,400 psi) to 1800 bar (26,100 psi). Hold pressure can be 40% to 80% of injection pressure, and hold times are relatively long to avoid sinks and to compensate for the high volume reduction when a semi-crystalline material passes from the melt state to the solid state. As is normal in injection molding, the screw should not be allowed to bottom at the forward limit of the injection stroke. The amount of melt remaining ahead of the screw in this condition is known as the cushion; for polypropylene this should be in the range 2 mm (0.079 in) to 6 mm (0.24 in) thick. Back pres-

Table 14.7 Typical barrel zone temperature settings for polypropylene.

Zone	Temperature setting (°C)	Temperature setting (°F)
1	150–210	300–410
2	210–250	410–480
3	220–250	430–480
4	220–250	430–480
Nozzle	240–260	465–500

sure during screw rotation can be in the range 100 bar (1450 psi) to 300 bar (4400 psi). Higher values result in better mixing of masterbatch or other additives, but will require the use of a valved nozzle to prevent drooling.

The principal parameters affecting the flow of plastics melt during injection are injection rate and melt temperature. Injection rate is directly controlled in closed-loop injection systems; the injection pressure in the filling phase is whatever is needed to generate the chosen rate. In open-loop systems, the pressure is chosen and the injection rate is uncontrolled. The viscosity of a plastics melt varies with shear rate and temperature, and shear rate is proportional to injection rate, so an uncontrolled injection rate is less than ideal. In other words, closed loop injection systems should be the norm for consistent results. The difficulty faced by those optimizing an injection molding project is to know whether it is more productive to improve melt flow by raising the melt temperature or increasing the injection rate (shear rate). The answer depends on the characteristics of the material.

The viscosity of a polypropylene melt is sensitive to shear rate but the extent of this sensitivity depends on the molecular weight distribution of the particular grade. Those with a wide molecular weight distribution respond the most to an increase in shear rate. For polypropylene materials as a class, it will be more effective to deal with mold

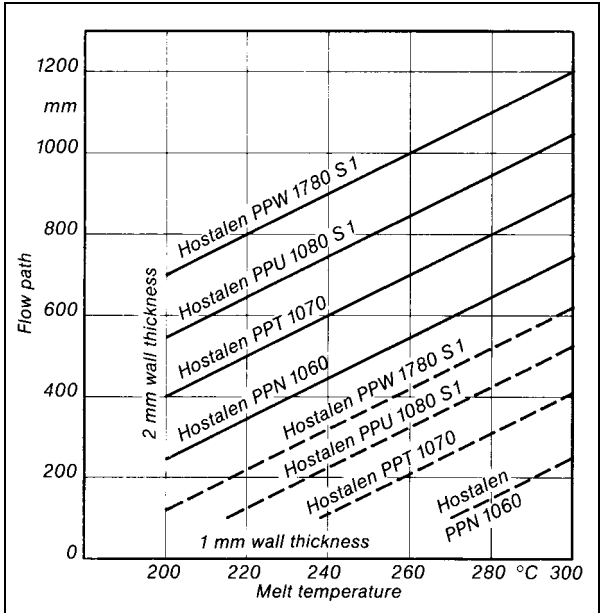


Figure 14.11 Flow path length as a function of melt temperature for various grades of Hoechst Hostalen polypropylene.

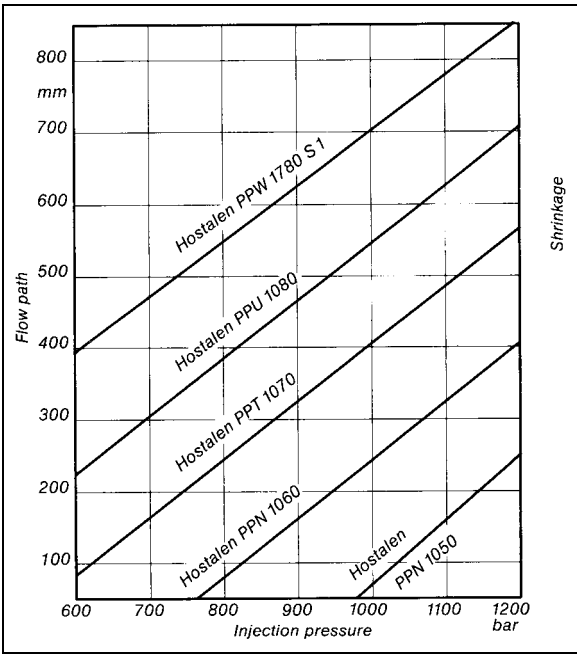


Figure 14.12 2mm thick flow path length as a function of specific injection pressure for various grades of Hoechst Hostalen polypropylene.

filling problems by increasing the injection rate rather than raising the melt temperature. Raising the mold temperature may appear to be an alternative strategy, but this has very little effect on flow provided injection rates are rapid enough to prevent the premature freezing of thin sections.

A practical measure of polypropylene flow under injection molding conditions is the flow path length. The graphs demonstrate the effects of melt temperature (Figure 14.11), injection pressure (Figure 14.12), and fillers and reinforcements (Figure 14.13, Figure 14.14) on the maximum flow path length obtainable with various grades of polypropylene.

14.3.2 Clamp

The clamp force requirement for a polypropylene injection molding is best established by the use of a computer flow simulation that will determine the pressure gradients throughout the cavities and feed system and will reflect the effect on pressure of the material characteristics and the many process parameters. The comparative accuracy of the figure means that only a small safety margin need be applied, and this in turn ensures that the injection molding machine selected is the smallest possible. Since hourly running costs are related to machine size, the effect is to minimize the production cost of the molding, and so it is worth paying attention to clamp force determination.

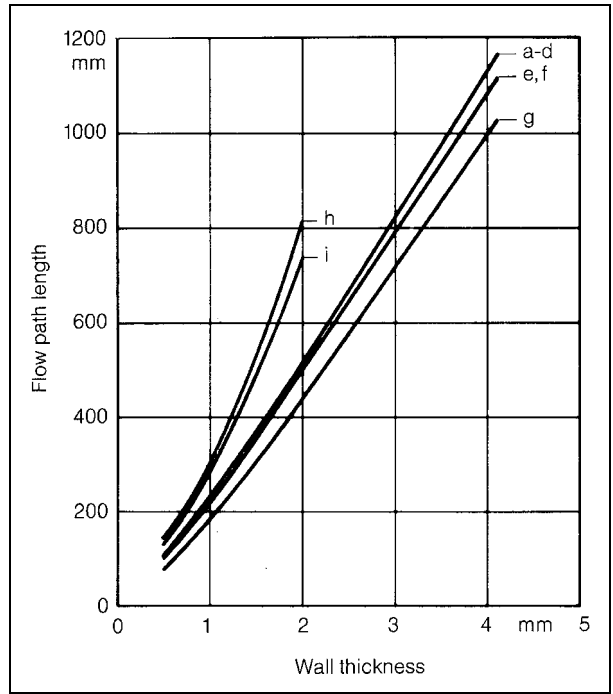


Figure 14.13 Flow path length as a function of wall thickness for various reinforced grades of Hoechst Hostacom polypropylene. Conditions: melt 250°C, mold 60°C, injection pressure 750 bar, injection rate 60% of maximum. Key: a = Hostacom M2 N02 20% talc filler, improved impact strength, b = Hostacom M2 N01 20% talc filler, c = Hostacom G2 N02 20% coupled glass fiber reinforcement, d = Hostacom G2 N03 20% glass micro-spheres, e = Hostacom M4 N01 40% talc filler, f = Hostacom G2 N01 20% glass fiber reinforcement, g = Hostacom G3 N01 30% coupled glass fiber reinforcement, h = Hostacom M1 U01 10% talc filler, i = Hostacom M4 U01 40% talc filler, improved flow .

Underestimation of the force requirement may lead to the choice of a machine with insufficient clamp force. If so, the mold will open slightly during injection, causing an overflow or flash as it is known, to be formed on the molding. The remedy is to use a machine with a greater clamp force, at a consequential cost disadvantage. If a computer simulation is not available, the chart (Figure 14.15) and table (Table 14.8) can be used to calculate the required clamp force but the margin of uncertainty will be greater and the use of a larger safety factor of some 25% to 50% is advisable.

To calculate clamp force:

- Find the longest flow path in the molding and divide it by the wall thickness. This gives the ratio of flow path length to thickness.
- Find the corresponding curve on the chart. If the ratio is not an exact match, either choose the next highest curve or interpolate a curve.

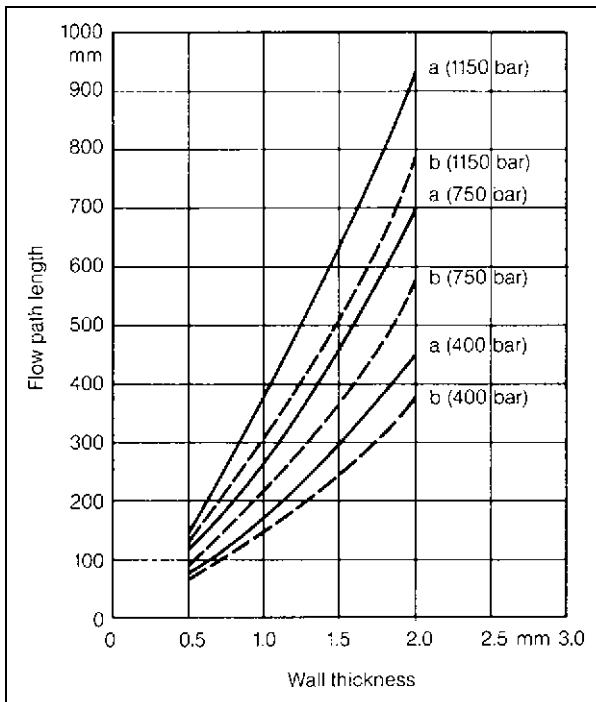


Figure 14.14 Flow path length as a function of wall thickness and injection pressure for talc filled grades of Hoechst Hostacom polypropylene. Conditions: melt 230°C, mold 60°C, injection rate 60% of maximum. Key: a = Hoechst Hostacom M1 U01 10% talc filler, b = Hoechst Hostacom M4 U01 40% talc filler, improved flow.

- Trace a vertical line from the wall thickness (mm) to the chosen curve. Where this cuts the curve, trace a horizontal line to the pressure axis and read off the cavity pressure (bar).
- Calculate the notional clamp force (kN) by multiplying cavity pressure (bar) by the mold projected area (cm²) and dividing by 100.
- Adjust the clamp force by multiplying the notional figure by the appropriate material factor from the table.
- The resulting force figure represents a molding of simple configuration. Moldings with complex flow paths and varying thicknesses will require a higher clamp force.

14.3.3 Shrinkage and warping

Polypropylene injection moldings shrink on and after removal from the mold. The magnitude of shrinkage ranges from 1.2% to 2.5%. To create the right dimensions in the molded part, the dimensions of the mold cavity must be increased by an amount known as the shrinkage allowance. Shrinkage is not only a matter of thermal expansion

Table 14.8 Material factors for clamp force determination.

Polymer	Material factor
LD polyethylene	1
Polystyrene	1
Polypropylene	1.0–1.2
HD polyethylene	1.0–1.3
Polyamide 11	1.2–1.4
Polyamide 12	1.2–1.4
Polyamide 6	1.2–1.4
Polyamide 6/10	1.2–1.4
Polyamide 6/6	1.2–1.4
ABS	1.3–1.5
PMMA	1.5–1.7
Polycarbonate	1.7–2
PVC-U	2

sion and contraction but must also take account of the fact that the injected melt is compressible at injection pressures. These pressures vary throughout the molded part and therefore so too does shrinkage. For semi-crystalline materials such as polypropylene, the effect is exaggerated by a sharp change in specific volume associated with crystalline fusion.

There is also a directional aspect to polypropylene shrinkage. The material shrinks more in the direction of flow than in the transverse direction. This is known as anisotropic shrinkage and is a consequence of the long-chain molecular structure which leads to a partial orientation and stretching of the chains during melt flow. The effect is more marked

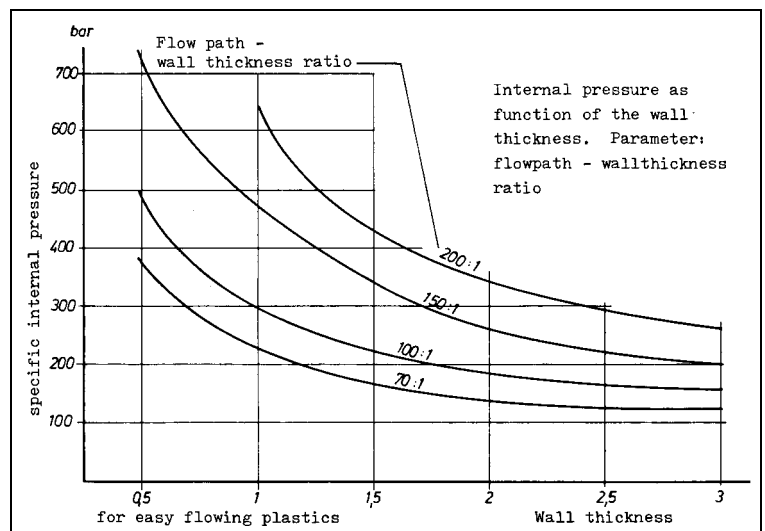


Figure 14.15 Chart for determination of clamp force.

Table 14.9 Some factors influencing polypropylene shrinkage.

Parameter	Increase	Maximum shrinkage variation (%)	Notes
Mold temperature	20°C to 90°C	+ 0.6	
Wall thickness	1mm to 6mm	+ 0.5	
Duration of holding pressure	up to 20 sec	- 0.3	min. wall thickness 2mm
Magnitude of injection/holding pressure	600 bar to 1400 bar	- 0.3	min. wall thickness 2mm
Melt temperature	220°C to 280°C	+ 0.3	
Melt flow rate	1 g/10 min to 50 g/10 min	- 0.3	

in polypropylenes with a wide molecular weight distribution and is at its least in grades that have a narrow distribution of molecular weight. The range of difference between the two shrinkage values in conventional grades of polypropylene is of the order of 0.1% to 0.5%. For controlled rheology grades the differential is much less, perhaps 0.03% to 0.05%. This is due to the particularly narrow molecular weight distribution of these grades. Differential shrinkage results in a distorted or warped molding. The remedy is to eliminate as far as possible the conditions that cause the differentials. Wall thicknesses should be constant, cooling uniform, and the various flow paths in the mold should be designed to fill at the same time and under the same conditions of pressure and shear rate.

Shrinkage is not an instantaneous effect. The greater part of shrinkage will be evident immediately on removal from the mold but further changes take place at a rapidly decelerating rate as the part cools completely throughout its thickness. During this time, crystallization and relaxation of internal stresses both continue slowly. The phenomenon is known as post shrinkage and may amount to about 1%. Consequently, measurements of critical dimensions should not be made sooner than 24 hours after molding. Changes may continue after 24 hours but the rate of change will be very slow at normal room temperatures.

As shrinkage is a function of temperature, pressure and shear rate, the injection molding conditions will also have a significant effect on the final dimensions of the part. Taken in combination, these considerations make it impossible to quote the molder or mold designer a single simple and precise shrinkage factor (Table 14.9, Figure 14.16). That in turn means it is difficult to injection mold polypropylene to precision tolerances.

The presence of fillers and reinforcements affects the shrinkage of polypropylene in different ways, depending on the nature of the additive. Particulate fillers such as talc or glass beads reduce the shrinkage to a value in the range 0.5% to 1.6%. The shrinkage differential is also reduced from near zero to about 0.15%, so these materials have less tendency to warp than unfilled polypropylenes.

Fibrous reinforcements such as glass also reduce the overall value of shrinkage but increase the differential shrinkage, and so increase the tendency to warp. The shrinkage of conventional glass grades is roughly 0.7% to 1.8% but that of coupled glass grades is much lower at about 0.4% to 1.2%. The effect is due to the very strong bond between coupled glass fibers and the polypropylene matrix. The increase in differential shrinkage is due to the tendency of the fibers to become partially oriented in the flow direction. This means that the fibers exert a much greater resistance to shrinkage in the flow direction than in the transverse direction. The differential for conventional glass fiber grades is about 0.3% to 0.5% but is much worse for coupled glass grades, rising to about 0.8%.

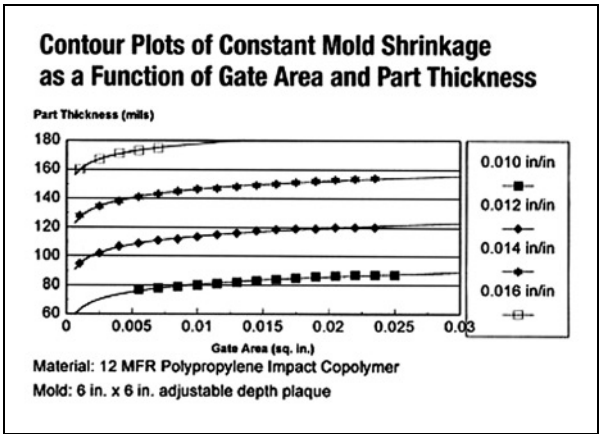


Figure 14.16 Shrinkage as a function of part thickness and gate area.

Post shrinkage of reinforced and filled polypropylenes is limited to about 0.5% or less.

14.3.4 Injection molding long-fiber reinforced grades

Experience has shown that polypropylene grades reinforced with long glass fibers (10 mm to 12 mm long) do not suffer as much fiber damage during injection molding as was first expected. Some degree of fiber damage is acceptable, provided the aspect ratio remains above a critical value. So to preserve the benefits of long-fiber reinforcement, the molding conditions should be chosen to minimize fiber fracture.

During plasticizing, the melt shear stress should be held as low as possible by using a low screw speed with a high melt temperature. The screw should be fitted with a ring non-return valve rather than the ball type. Nozzles, runners and gates should be large to minimize shear. A direct sprue gate is ideal. Screw and mold wear is, if anything, less than that experienced with short-fiber glass reinforced materials. This is due to the relatively small number of fiber ends present in long-fiber grades.

14.3.5 Injection molding metallocene grades

Metallocene grades of polypropylene are very new and are not yet extensively used in injection molding, so process guidelines are slow to emerge. The first indications are that high injection speeds and packing pressures should be used. Back pressure should be as low as possible. Barrel temperatures should be substantially uniform, apart from the feed zone. The temperature range is 175°C to 290°C. Mold temperatures should be as low as possible with 10°C as a suggested ideal.

14.3.6 Troubleshooting

The complexity of the injection molding process, and the inter-dependence of the many variables involved, means that any molding defect may have several different causes, of which more than one may be present at any given time. Consequently a remedy that cures one fault may engender another. Attempts to describe cause and effect in terms of computer expert systems have so far met with at best very limited success. The conclusion is that injection molding troubleshooting is a job for the expert. Provided these limitations are understood, the trouble shooting chart (Table 14.10) will provide a useful guide for problem solving.

Table 14.10 Injection molding trouble shooting chart. [1049]

Problem	Possible cause	Suggested remedy
Short shots	Insufficient feed	Increase
	Insufficient pressure	Increase
	Melt temperature too low	Lengthen cycle Increase temperature gradually Increase screw speed and back pressure
	Injection time too short	Increase
	Nozzle cold on start-up	Fit nozzle heater
	Mold too cold	Reduce coolant flow Fit mold temperature controller
	Feed system too small	Enlarge sprue or runner or gate
	Air trapped in mold	Add or clean vents
	Plasticizing capacity inadequate.	Increase cycle time Use a larger machine
	Unbalanced cavity in multi-cavity mold	Adjust runner or gate size
	Excessively thin region	Redesign part

Table 14.10 Injection molding troubleshooting chart. [1049] (continued)

Problem	Possible cause	Suggested remedy
Sink marks	Melt temperature too high	Reduce barrel temperatures
	Insufficient material injected	Increase feed Raise barrel temperatures Increase mold temperature Enlarge gates
	Insufficient dwell time	Increase
	Premature gate freezing	Enlarge gate Increase mold temperature
	Sharp variations in wall thickness	Redesign part
	Wrong gate location	Relocate
	Part ejected too hot	Increase cooling time Use nucleated grade
	Cavity pressure too low	Increase Raise barrel temperatures Increase mold temperature Enlarge gate
Voids	Volatiles from overheated material	Reduce heating
	Condensation on granules	Pre-dry Improve storage
	Premature freezing of flow path to thick section	Increase pressure Increase mold temperature Use nucleated grade Enlarge gates
Surface defects near gate	Mold too cold	Increase mold temperature Increase pressure Increase injection speed
	Mold too hot	Cool mold near gate
Flash	Excessive injection pressure	Reduce pressure Reduce runners
	Excessive melt temperature	Reduce heating
	Mold parting face faulty	Repair mold
	Insufficient clamp force	Increase Use a larger machine
	Foreign matter on mold parting face	Clean mold
	Flow restriction in one or more cavities of multi-cavity mold	Identify and remove
Flow marks	Melt temperature too low	Increase heating
Weld lines	Incorrect gate location	Relocate
Bad surface finish	Incorrect gate type	Adjust
	Injection pressure too low	Increase
	Inadequate venting	Vent cavity
	Mold cavity soiled	Clean mold
	Mold temperature too low	Increase
	Flow length too great	Relocate gate Increase number of gates
	Excessive use of mold lubricant	Mold lubricant not recommended

Table 14.10 Injection molding trouble shooting chart. [1049] (continued)

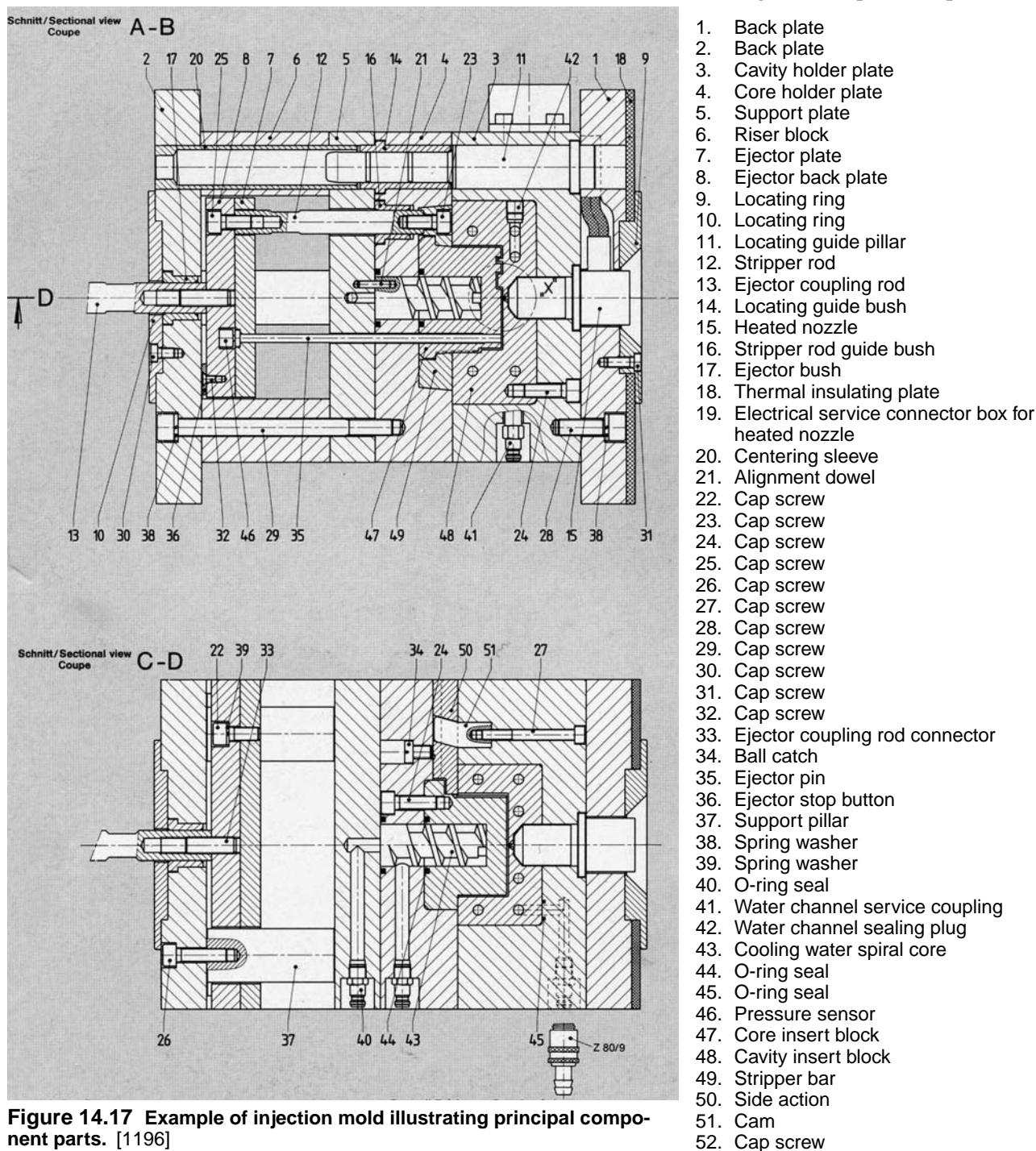
Problem	Possible cause	Suggested remedy
Brittleness	Melt temperature too low	Increase heating
	Mold too cold	Increase mold temperature
	Melt degraded by excessive heating	Decrease heating
	Material contaminated	Clean hopper and barrel
	Incorrect part design	Redesign part
	Excessive use of regrind	Reduce proportion of regrind
Warping	Melt temperature too low	Increase heating
	Incorrect part design	Redesign part
	Overpacking near gate	Reduce shot volume Reduce injection pressure Reduce injection time Reduce heating Check runner and gate sizes
	Sharp variations in wall thickness	Redesign part
	Flow length too great	Relocate gate Increase number of gates
	Unbalanced multiple gates	Relocate gates Balance feed system
	Part ejected too hot	Increase cooling time Use nucleated grade
	Inadequate or badly located ejectors	Modify mold
	Temperature variations between the mold halves	Adjust cooling circuits Modify mold
Silver streaks	Melt temperature too low	Increase heating
	Mold too cold	Increase mold temperature
	Condensation on mold	Dry mold Increase mold temperature
	Entrapped volatiles	Pre-dry material Improve storage Vent mold
Nozzle drool	Excessive nozzle temperature	Reduce heating
	Excessive melt temperature	Reduce heating Purge barrel
Burn marks	Incorrect filling pattern	Relocate gate Improve venting
Parts sticking	Molding too hot	Increase cooling
	Insufficient draft on side walls	Increase draft angle
	Excessive injection pressure	Decrease
	Cavity finish poor	Polish mold
	Cores misaligned by injection pressure	Redesign part Relocate gate

14.4 Injection molds

14.4.1 Introduction

The injection mold performs two vital functions. It defines the shape of the molded part, and it acts as a heat exchanger to cool the plastics material from melt temperature to ejection temperature. It must be very robustly engineered to withstand injection and clamping forces, it must operate automatically at high speed, and it must be built to very high standards of precision and finish. The mold also has

other less obvious influences on the finished part. The dimensions and properties of the molding are greatly affected by shear rates, shear stresses, flow patterns, and cooling rates. Some of these are affected by both mold and machine; others are almost exclusively a function of the mold. These factors combine to make the injection mold a costly item. Modern technologies in the form of concurrent engineering, computer-aided analysis of flow and cooling, high-speed and computer-controlled machining can help to keep the cost



down. So too can the use of standard mold components that enjoy economies of scale and specialization. Even so, mold costs frequently dismay purchasers of moldings and there can be pressure to cut costs by reducing mold quality. This is a false economy and will almost always result in a more expensive molding. There is no substitute for a quality mold.

14.4.2 Injection Mold Components

The figure (Figure 14.17) illustrates the principal components used in the construction of an injection mold.

The sequence of operations (Figure 14.18) for a typical mold is:

- Plastics material is injected into the closed mold.
- The mold remains closed while the molding cools. The mold temperature is controlled by a coolant fluid (generally water or oil) which is pumped through cooling channels. Even if the mold is heated relative to ambient temperature it is still cool in relation to the plastics melt temperature.
- The mold opens, leaving the molding attached by shrinkage to the core. During opening the side action is retracted by a cam to release an undercut on the molding.
- The ejector plate is moved forward, causing ejector pins and stripper bars to push the molding off the core.
- The ejector plate returns and the mold closes, ready for the next cycle.

14.4.3 Injection Mold Types

Every molded part is different and so every mold is a one-off. Nevertheless, it is possible to distinguish some standard features and types. All are suitable for use with polypropylene. The principal types are two-plate, three-plate, and stack molds. A further distinction concerns the feed system which can be either the cold or hot type. These classifications overlap. A three-plate mold will have a cold runner feed system, and a stack mold will have a hot runner system. Two plate molds can have either feed system.

14.4.3.1 2-plate

The two-plate mold has more than two plates in its construction. The description means that the mold opens or splits into two principal parts (Figure 14.19). These are known as the fixed or injection half which is attached to the machine fixed platen, and the moving or ejection half which is attached to the moving platen. This is the simplest type of injection mold and can be adapted to almost any type of molding. The cavities and cores that define the shape of the molding — these are sometimes known as the impressions — are so arranged that when the mold opens, the molding remains on the ejection half of the mold. In the simplest case, this is determined by shrinkage that causes the molding to grip on the core. Sometimes it may be necessary to adopt positive measures such as undercut features or cavity air blast to ensure that the molding remains in the ejection half of the mold.

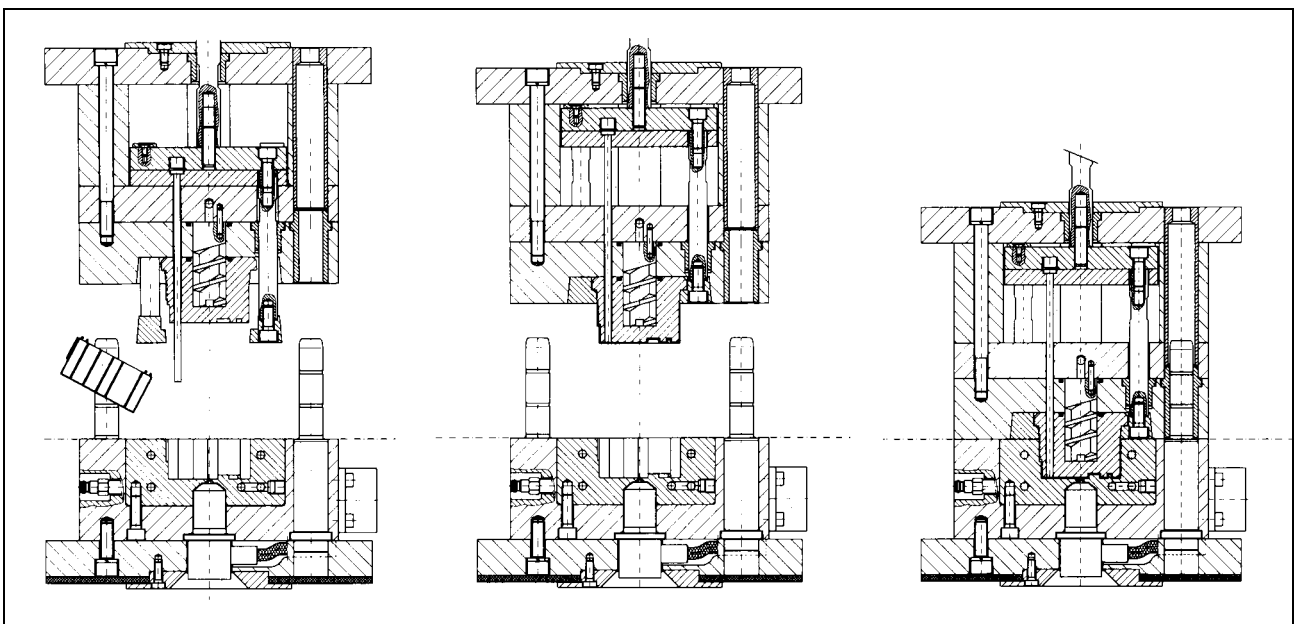


Figure 14.18 Sequence of mold operations.

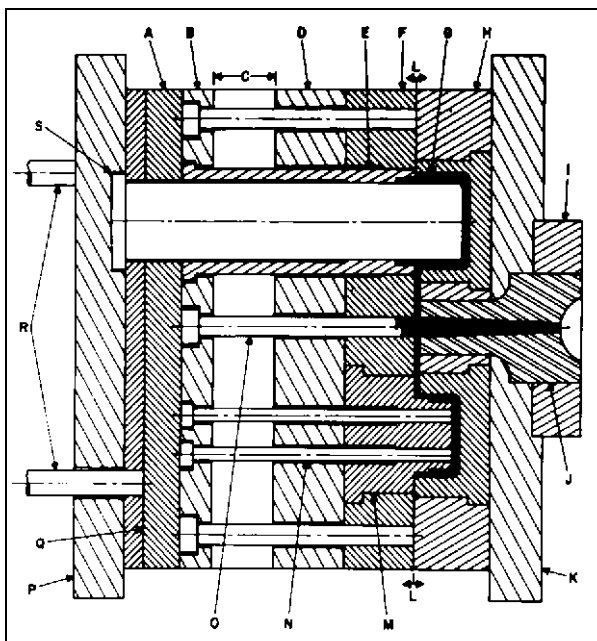


Figure 14.19 Schematic of 2-plate mold.
A-Knockout plate, B-Ejector retainer plate, C-Ejector travel, D-Support plate, E-Sleeve-type ejector, F-Rear cavity plate, G-Cavity, H-Front cavity plate, I-Locating ring, J-Sprue bushing, K-Clamping plate, L-Parting line, M-Core or force, N-Ejector pin, O-Sprue puller, P-Clamping plate, Q-Retainer plate, R-Knockout pins, S-Core or force pin.

14.4.3.2 3-plate

The 3-plate mold is so called because it splits into three principal linked parts when the machine clamp opens (Figure 14.20). As well as the fixed and moving parts equating to the 2-plate mold there is an intermediate floating cavity plate. The feed system is housed between the fixed injection half and

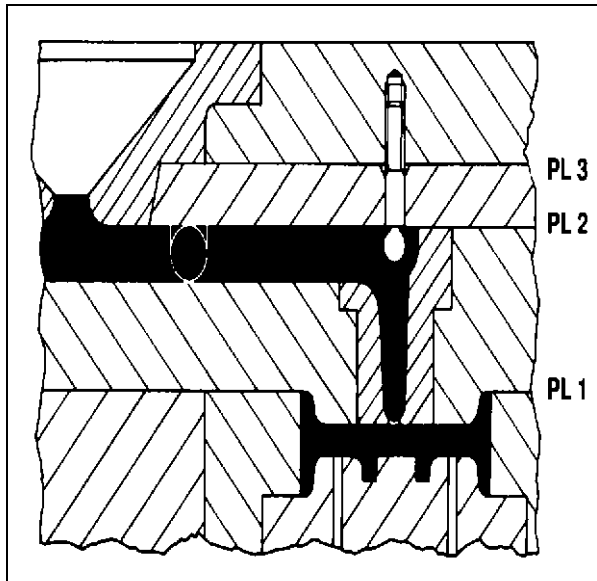


Figure 14.20 Schematic of 3-plate gate.

the floating cavity plate. When the mold opens it is extracted from the first daylight formed by these plates parting. The cavity and core is housed between the other side of the floating cavity plate and the moving ejection part of the mold. Moldings are extracted from the second daylight when these plates part. The mold needs separate ejection systems for the feed system and the moldings. Motive power for the feed system ejector and the movement of the floating cavity plate is derived from the clamp opening stroke by a variety of linkage devices. The molding ejection system is powered normally by the injection machine ejection system.

The 3-plate mold is normally used when it is necessary to inject multiple cavities in central rather than edge positions. This is done for flow reasons, to avoid gas traps, ovality caused by differential shrinkage, or core deflection caused by unbalanced flow. This type of mold also has the advantage of automatically removing (degating) the feed system from the molding. The disadvantages are that the volume of the feed system is greater than that of a 2-plate mold for the same component, and that the mold construction is more complicated and costly.

14.4.3.3 Stack

The stack mold also features two or more daylights in the open position. Two daylights is the normal form (Figure 14.21) but up to four are known. The purpose of the stack mold is to increase the number of cavities in the mold without increasing the projected area and hence the clamp force required from the injection molding machine. This is done by providing cavities and cores between each of the daylights. Provided the projected area at each daylight is the same, opposed components of opening thrust from each daylight cancel out, leaving the total mold opening force no

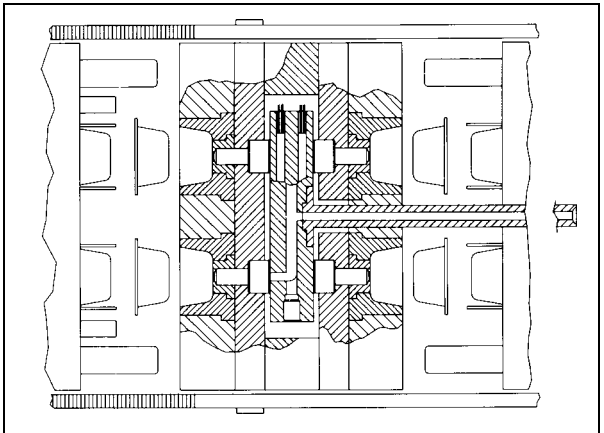


Figure 14.21 Schematic of stack mold.

greater than that developed in a single daylight. The cavities are fed by a hot runner system deployed in the floating cavity plate. Separate ejection systems are required for each daylight. The mold engineering and hot runner control systems are complicated and become much more so when there are more than two daylights present. Stack molds are normally used for high volume production of relatively small and shallow components such as closures for packaging applications.

14.4.4 Injection Mold Feed system

The feed system is the name given to the flow melt passage in the mold, between the nozzle of the injection molding machine and the mold cavities. This apparently utilitarian feature has a considerable effect on both the quality and economy of the molding process. The feed system must conduct the plastics melt to the cavity at the right temperature, must not impose an excessive pressure drop or shear input, and should not result in non-uniform conditions at the cavities of multi-impression molds. The feed system is an unwanted by-product of the molding process, so a further requirement is to keep the mass of the feed system at a minimum to reduce the amount of plastics material used.

This last consideration is a major point of difference between cold and hot runner systems. The cold runner feed system is maintained at the same temperature as the rest of the mold. In other words, it is cold with respect to the melt temperature. The cold runner solidifies along with the molding and is ejected with it as a waste product in every cycle. The hot runner system is maintained at melt temperature as a separate thermal system within the cool mold. Plastics material within the hot runner system remains as a melt throughout the cycle, and is eventually used on the next or subsequent cycles. Consequently, there is little or no feed system waste with a hot runner system. Effectively, a hot runner system moves the interface between the machine plasticizing system and the mold to a point at or near the cavities. In a cold runner system, the interface is at the outside surface of the mold, at a point between the machine nozzle and the sprue bush.

14.4.4.1 Cold runner

Cold runner feed systems include three principal components; sprue, runner, and gate. The sprue is a tapered bore in line with the axis of the injection unit, that conducts the melt to the parting line of the mold. The runner is a channel cut in a parting

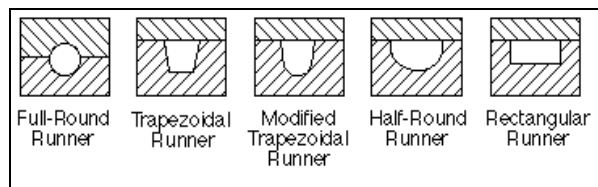


Figure 14.22 Common runner configurations. [1221]

face of the mold to conduct melt from the sprue to a point very close to the cavity. The gate is a relatively small and short channel that connects the runner to the cavity. The gate is the entry point of the melt into the molding cavity.

Runners are produced in a variety of cross-sectional configurations (Figure 14.22), but not all of them perform equally well. The best shape for the runner itself is a full-round section, cut in both halves of the mold. This is the most efficient form for melt flow without premature cooling. There are some instances when it is desirable to cut the runner only in one half of the mold, either to reduce the machining cost or where it is mechanically necessary over moving splits. In this case, the preferred runner sections are trapezoidal or modified trapezoidal. The half-round runner provides only a restricted flow channel combined with a large surface area for cooling and consequently is not to be recommended.

The concept of the hydraulic diameter (D_H) provides a quantitative means of ranking the flow resistance of the various runner configurations. Hydraulic diameter is calculated from an expression chosen to give a full-round runner a value of $1D$, where D is the runner diameter:

$$D_H = 4A/P$$

where A = cross-sectional area and P = perimeter

The resulting values for equivalent hydraulic diameter (Figure 14.23) clearly demonstrate the superi-

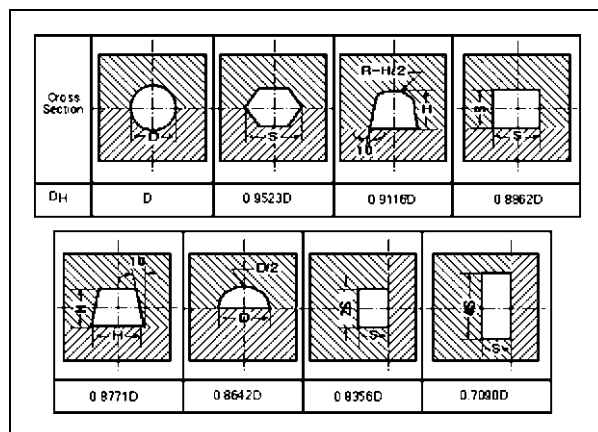


Figure 14.23 Equivalent hydraulic diameters for common runner configurations. [1221]

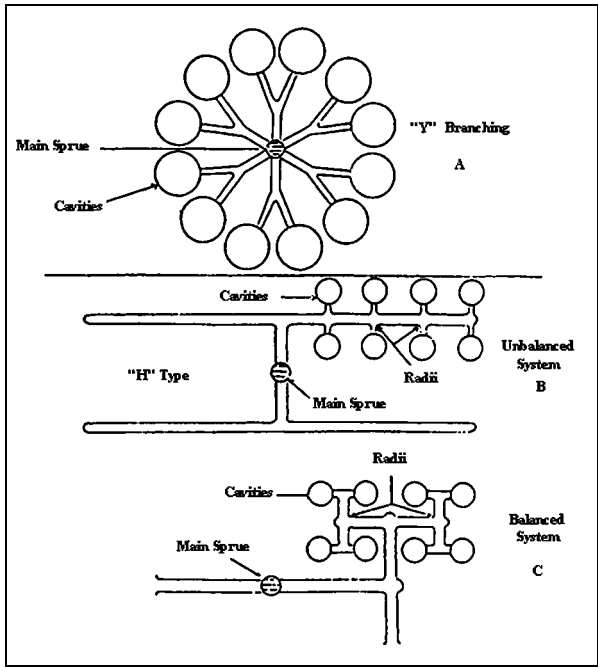


Figure 14.24 Balanced and unbalanced runner layouts.

ority of the full-round design for runners cut in both halves of the mold and the modified trapezoidal design for runners cut in one half of the mold.

Runner layouts should be designed to deliver the plastics melt at the same time and at the same temperature, pressure and velocity to each cavity of a multi-cavity mold. Such a layout is known as a balanced runner (Figure 14.24). A balanced runner will usually consume more material than an unbalanced type, but this disadvantage is outweighed by the improvement in the uniformity and

quality of the moldings. Balance in a multi-cavity mold with dissimilar cavities (known as a family mold) can be achieved by careful variation of runner diameter in order to produce equal pressure drops in each flow path. Such balancing can only be achieved efficiently by the use of computer flow simulations, and this method really should now be the norm for injection mold design.

If flow simulation software is used, runner dimensions will be calculated precisely and can then optionally be adjusted to a standard cutter size. If a simulation is not available, the following guidelines (Figure 14.25) suggest suitable runner sizes for use with polypropylene. These are given as a function of wall thickness and may need to be adjusted for parts that are thicker than 4 mm or thinner than 2 mm. In any case, fine tuning may be necessary during mold trials. The easiest way to do this is to start with small runners and enlarge them if necessary.

14.4.4.2 Sprue

The sprue (Figure 14.26) is often the thickest part in an injection molding shot and in extreme cases may influence the cycle time. Since the sprue is a waste part, this should never be allowed to happen. The reason that it sometimes does is that there is little control over the dimensions of the sprue. The length is fixed by the thickness of the fixed mold half while the diameter is largely a function of the machine nozzle bore and the necessary release taper. Sometimes the sprue can serve a useful function as a gripping point for an automated shot han-

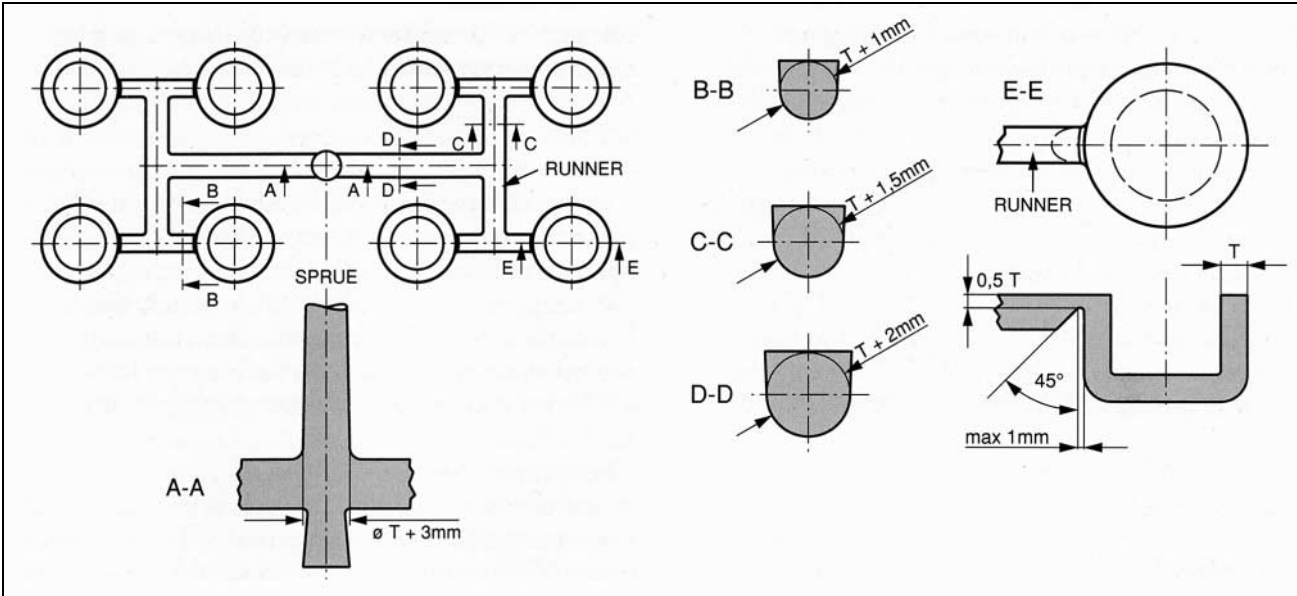


Figure 14.25 Suggested approximate sprue and runner sizes.

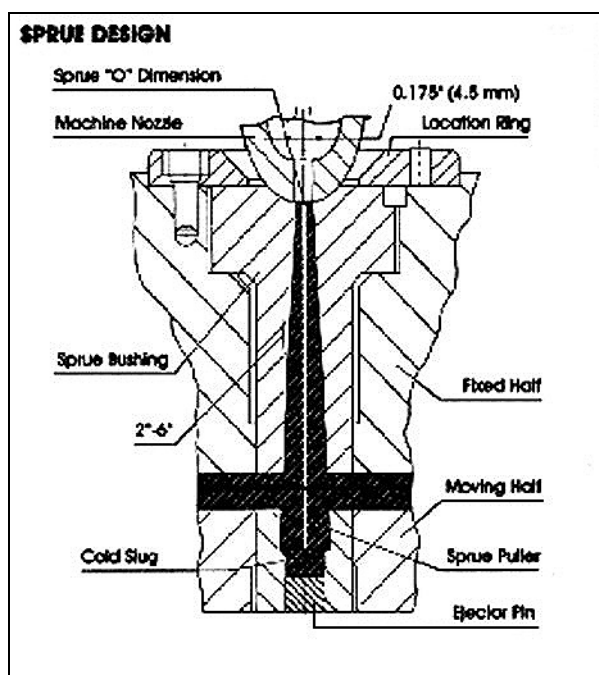


Figure 14.26 Typical cold sprue design.

dling system, but the answer in most cases is to eliminate the cold sprue by means of a heated sprue bush (Figure 14.27) that serves as a limited hot runner device. In this case, the material in the bush remains as a melt while the cold runner system is injected through a vestigial sprue. Elimination of the sprue typically saves 3 grams to 5 grams of material waste per cycle.

14.4.4.3 Gates

The gate is the region of the feed system between the runner and the cavity. It is the entry point by which the plastics melt enters the cavity and is an important element of the mold. Its position and dimensions have a considerable influence on the finished molding. The position of the gate or gates directly influences flow paths in the cavity, and so has a major bearing on issues such as filling pressure, weld line quality, and gas traps. Gate positions must be judged individually for each molding case. An

experienced practitioner can usually assess the best gate position for a relatively simple part geometry but for complex parts, computer-aided flow analysis is preferred for gate positioning.

Gate positions should be chosen with these general recommendations in mind:

- Gate near a thick section to ensure that it can be packed out
- Position the gate where the gate scar or witness mark will not be cosmetically objectionable
- Position the gate where it can be easily removed with cutting tools
- Position the gate for flow symmetry in symmetrical parts
- Gate to minimize gas traps and weld lines
- Gate so that unbalanced flow does not take place around cores
- Do not place the gate at a point where high stresses or high packing could cause problems
- Position the gate so that flow impinges on a mold surface rather than jets into a void
- Position the gate to minimize shrinkage differentials

The gate is usually small in relation both to the molding and the upstream feed system. There are two principal reasons for this. The gate acts as a thermal valve that seals the filled mold cavity from the feed system. When the gate freezes, no more flow can take place. A very heavy gate would be slow to freeze and would possibly allow compressed melt to flow back out of the cavity and into the feed system, so one aim of gate design is to find a size that will remain open during the injection packing phase and freeze off immediately thereafter. The other reason for a small gate is so that the feed system can be easily removed from the molding, leaving little trace of its presence.

Flow conditions in the gate are extremely severe. The melt is accelerated to a high velocity and is subjected to a high shear rate. This is the main reason for keeping gates short. The gate length is often referred to as the land length; for polypropylene the dimension should be about 0.030 in or 0.75 mm. If the gate land is very short, there will be a weak section in the mold between the runner and cavity, and there will be insufficient clearance to use cutters for gate removal. During the passage of the melt through the gate frictional heating is likely to occur and indeed is sometimes exploited in the design of feed systems for heat-sensitive

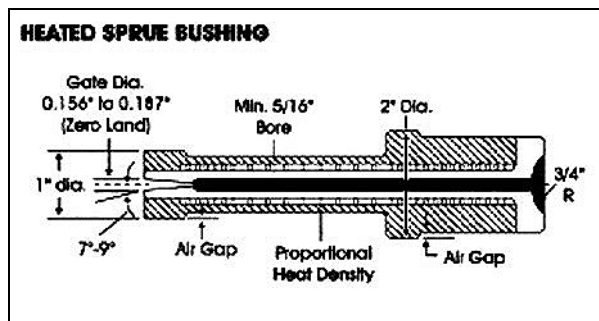


Figure 14.27 Example of heated sprue bush.

materials. Here the strategy is to keep barrel temperatures low and generate additional heat at the last moment in the feed system.

Many different gate types (Figure 14.28) have evolved to deal with a variety of molding needs. Some of these are associated with particular geometries. For example, diaphragm and ring gates are usually employed for parts with a cylin-

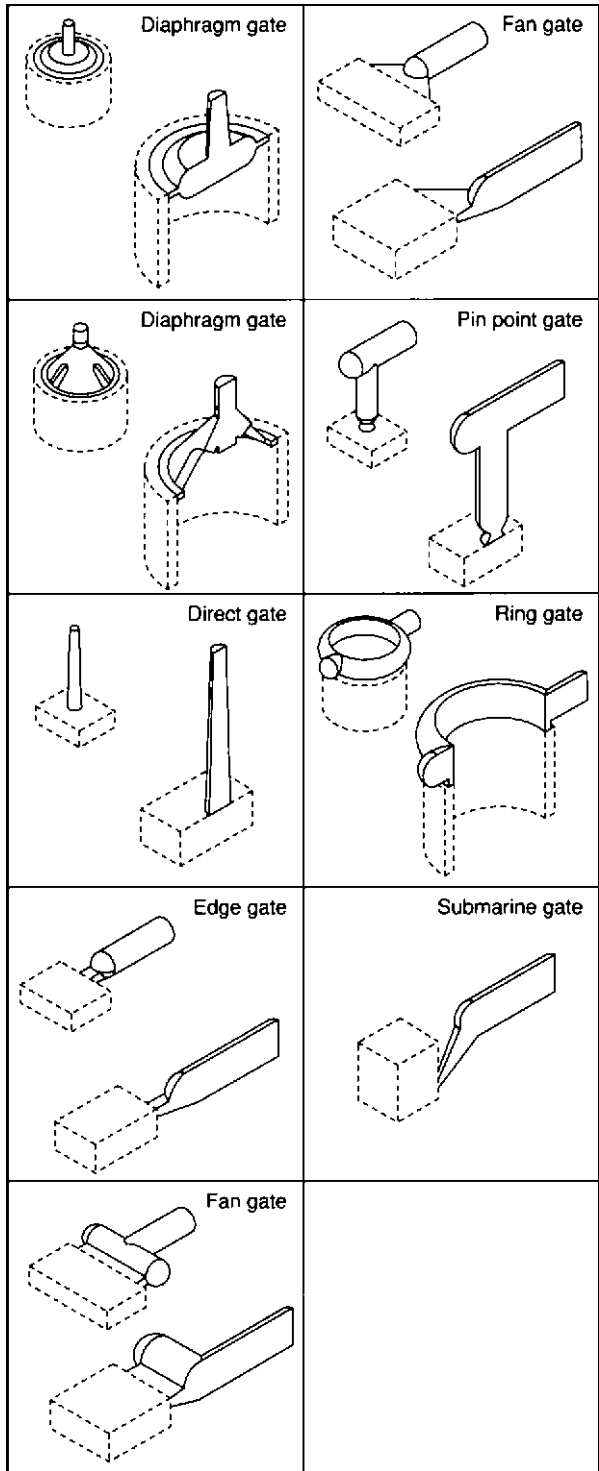


Figure 14.28 Examples of various gate types.

drical form. The pin-point gate is normally used in 3-plate molding. The commonest gate type is the edge gate. The edge gate is usually square or rectangular in cross section and is cut in just one parting face of the mold. Circular section gates are also used but must be cut equally in both parting faces. Semi-circular section gates are not recommended. Gate dimensions depend on product geometry and are frequently adjusted by trial and error during the testing of a new mold. The only practical way to do this is to start with a small gate and gradually enlarge it. As a rough rule, the gate size for polypropylene should be about half the maximum wall thickness of the molding, and should not be less than 0.030 in or 0.75 mm. This dimension is the diameter of a full-round gate or the inscribed circle of a square gate.

Simple large area parts in single-cavity molds may be gated by running the sprue directly into the cavity. This is known as sprue gating or direct sprue gating. The gate must be removed in a subsequent machining operation that leaves a witness mark. The sprue gate is perhaps the least sophisticated way of dealing with this type of molding. Fan gates are preferred for thin-walled parts of relatively large area. The flash gate, a variant of the fan gate, is used for thin-walled parts that would be difficult to fill from individual gates at any point. The flash gate is very wide and shallow so that a large flow area is combined with a short freeze time. Ring and diaphragm gates are similar in concept to the flash gate. They are normally used to obtain cylindrical parts free of weld lines and core shift caused by unbalanced flow.

The submarine gate, also known as the tunnel gate, is cut into the one half of the mold rather than on a parting face. This constitutes an undercut which is freed on ejection by the runner and gate flexing. The advantage of the submarine gate is that the feed system is automatically separated from the mold by the act of ejection that shears the gate off. Because polypropylene is not a highly rigid material, the inclination of the submarine gate is not critical; angles of 30° to 40° will be suitable. The winkle or cashew gate is a variant in which the gate is machined in a curved form and is suitable only for flexible grades. A further gate type known as the tab gate is used to prevent jetting into an open cavity or when some defect is expected close to the gate. The tab is a small extension on the molding which is fed at right angles to its axis by an edge gate; the tab is later removed from the finished part.

14.4.4.4 Hot runner

Hot runner systems maintain the feed channels in a permanently molten state and so eliminate the waste associated with a solidified cold feed system. Another advantage is that the pressure drop through the feed system is less than that of a comparable cold runner arrangement. The principal disadvantage is the need to maintain two very different temperature regimes within the mold. The hot runner system in a polypropylene mold may be operating at 260°C in close proximity to mold cavities at 20°C . This results in difficult problems of temperature control and differential expansion. The cost of a hot runner mold is also much greater than that of the cold runner equivalent. However, the important point is not the cost of the mold but that of the molding and here hot runner molds have the advantage. Unless order quantities are low or frequent color changes are required, there are grounds to prefer the hot runner mold. Processors are still often deterred by control and engineering fears associated with hot runners, but there has been great progress in this area, and very sophisticated and reliable designs are now available as stock components. Most manufacturers of hot runner components now offer completely engineered systems that free the molder and mold builder from design responsibility. Traditionally, cold runner molds have been the norm and hot runners the exception but progress has been such that the project concept really should now start from the opposite premise.

The heart of a hot runner system (Figure 14.29) is the manifold. This is a distribution block containing flow channels maintained at melt temperature. The channels distribute the melt from the single entry point at the sprue to multiple outlets at nozzles that feed individual cavities in a multi-cavity mold or serve as multiple gates in a single

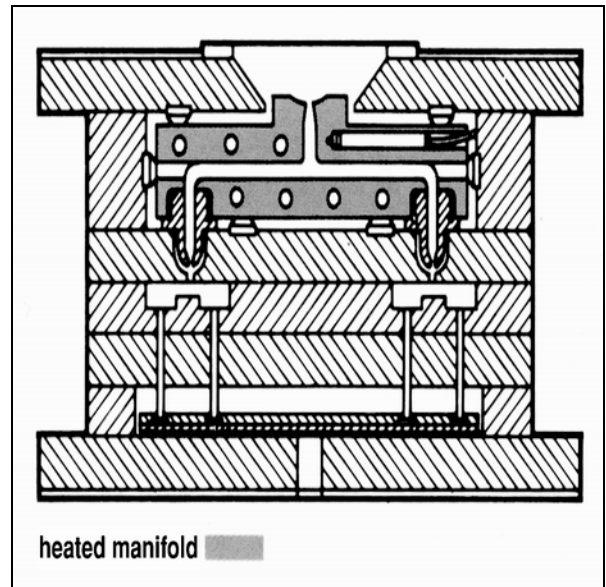


Figure 14.29 Schematic of hot runner mold.

large cavity. The latter case is one of the most important applications of hot runners; multiple gates allow the flow lengths in a large part to be brought within easily manageable proportions. The same strategy also limits the necessary clamp force.

Contact between the hot manifold and the remainder of the cool mold must be kept to a minimum to prevent heat flow. This is normally achieved by the use of air gaps that also allow for expansion, but care must be taken in the design to ensure that the mechanical strength of the mold remains adequate to deal with molding and clamping forces. The heat transfer problem is reduced with internally heated hot runners but the disadvantage is the relative inefficiency of the annular flow channel. These channels have higher pressure drops than unobstructed channels and are also prone to “slow flow” areas where material may stagnate and decompose. Internally heated hot runners are not on the whole recommended for

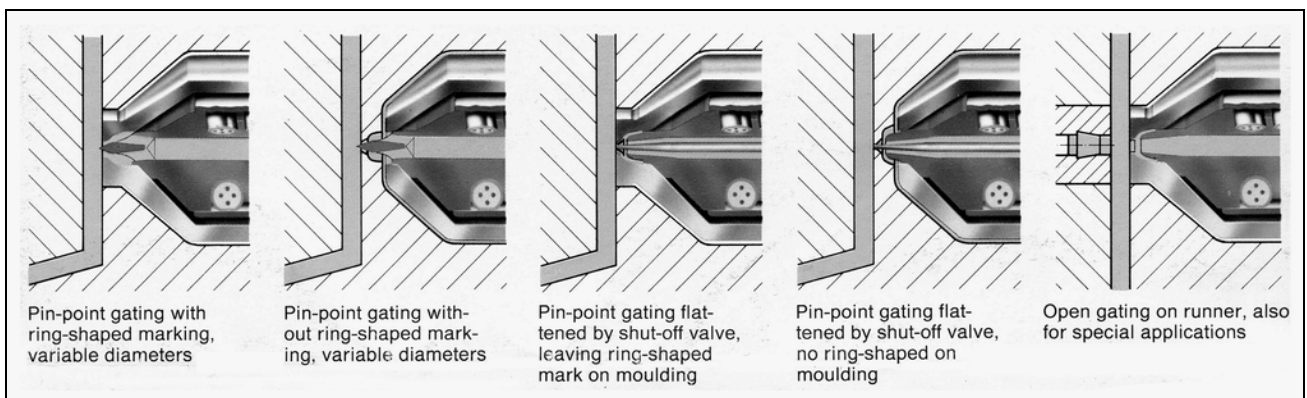


Figure 14.30 Some types of direct hot runner gate.

use with polypropylene.

A primitive variant of the hot runner is known as an insulated runner. This employs an unheated manifold with very large runners of 20 mm to 35 mm (0.75 in to 1.375 in) diameter, and relies on the poor thermal conductivity of plastics to ensure that a flow channel in the center of the large runner always remains molten. The insulated runner mold is not capable of precise and consistent control and is now rarely seen.

The connection between the hot runner manifold and the cavity is made by means of a hot nozzle that may operate in conjunction with a surrounding bushing. A wide variety of nozzle types allow for many gating options (Figure 14.30, Figure 14.31), with or without witness marks. Hot runner nozzles may be provided with shut-off valves for precise control of flow. In recent years, great progress has been made in the design of hot runner nozzles for small and closely spaced cavities. These designs allow one nozzle to feed a number of cavities, and also permit gating options that are almost undetectable on the finished part.

Polypropylene is not a particularly demanding material for hot runner applications. Most recommendations would be good practice with any thermoplastic. The heating power for manifolds should be at least 60 to 80 watts per cubic inch of

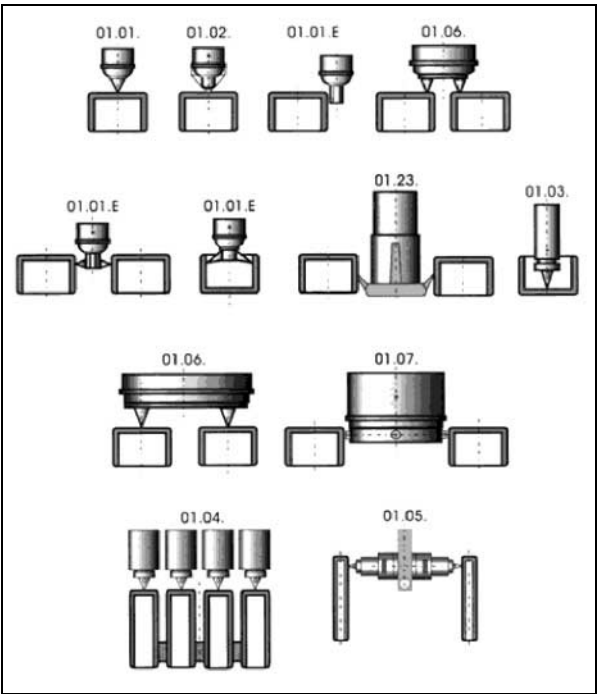


Figure 14.31 Advanced hot runner gates.

steel, and heaters should be positioned to eliminate hot and cold spots. Manifold flow channels should be at least 12 mm (0.5 in) in diameter. Large manifolds and high shot volumes will need bigger channels. Flow channels should be streamlined to prevent slow or stagnant flow. Corners should be radiused by contoured end plugs. The manifold air

Table 14.11 Comparison of properties of some mold construction materials.

Alloy type	Alloy UNS number	Thermal conductivity (W/m.K)	Rockwell hardness	Tensile strength (MPa)
STEEL				
Type 420 stainless steel	S42000	24.9	C27 — C52	863–1725
H-13 tool steel	T20813	24.9	C38 — C54	1421
P-20 tool steel	T51620	38.1	C28 — C50	1007
ALUMINUM				
Type 6061 T6	A96061	166.9	B60	276
Type 7075 T6	A97075	129.8	B88	462
COPPER				
Aluminum bronze	C62400	62.3	B92	725
BeCu — high hardness	C17200	104.8	C41	1311
BeCu — Moderate hardness	C17200	131.0	C30	1173
BeCu — High conductivity	C17510	233.6	B96	759
Cr — Hardened copper	C18200/18400	325.5	B60 — B80	352–483
NiSi — Hardened copper	C64700	162.6	B94	725
NiSiCr — Hardened copper	C18000	216.3	B94	690

gap should be at least 1.5 mm (0.62 in). Manifold support pads should have minimal surface contact and should be furnished in materials of relatively low thermal conductivity such as stainless steel or titanium. Precise temperature control is necessary for consistent results. The temperature of the manifold block should be uniform throughout. Each nozzle should be provided with individual closed-loop control.

14.4.5 Injection Mold Features

14.4.5.1 Materials

Injection molds are subject to rigorous requirements that have a direct bearing on the materials of construction (Table 14.11). Mold materials must withstand high injection pressures and clamp forces. They must be good thermal conductors, easy to machine, and be capable of reproducing fine detail and taking a high polish. They must be resistant to corrosion, abrasion, and wear. The traditional answer has always been steel and over the years the choice of alloyed and sintered steels

available to the mold maker has steadily expanded. Some are used only in specialist applications while others are generally used just for specific parts of the mold. Indeed, the average modern injection mold will contain a number of different steel types, some in the “as machined” state and others in a hardened and tempered condition (Table 14.12).

The choice of alternatives to steel is also growing, and the principle candidates are aluminum and copper alloys. There are two main reasons for using one of these materials in place of steel. They are generally softer and easier to machine. This speeds up mold production and reduces costs. The second reason is that they have much greater thermal conductivity than steel. This property can be exploited in areas of the mold where it is difficult to engineer adequate cooling channels or when a high rate of heat transfer is required for rapid cycling. The principal disadvantage is that these materials are much less hard and strong than steel alloys. Molds using aluminum and copper alloys are far more prone to damage

Table 14.12 Applications of principal mold steels.

Type	Characteristics	Werkstoff number	DIN description	Rockwell hardness	Applications
Medium carbon steel		1.1730	C45 W3	C10	Unhardened parts Back plates Cavity and core holder plates
Pre-hardened sulfur-free tool steel	For high compressive stresses. Good for spark erosion. Not recommended for high polish.	1.2311	Cr Mn Mo7	C32	Cavity and core holder plates Cavity and core inserts
Pre-hardened sulfur-free tool steel	For high compressive stresses. Good for spark erosion.	(AISI P20)		C30 — C32	Cavity and core holder plates Cavity and core inserts
Pre-hardened tool steel	For high compressive stresses. Not recommended for high polish.	1.2312	40 Cr Mn MoS 86	C32	Cavity and core holder plates Cavity and core inserts Support plates
Through-hardening tool steel	High toughness. High resistance to wear and corrosion. Suitable for mirror-finish polish.	1.2767	X45 Ni Cr Mo4	C52 — C56	Cavity and core inserts
Pre-hardened stainless steel	High resistance to corrosion. Suitable for mirror-finish polish.	1.2316	X36 Cr Mo 17	C30	Cavity and core inserts
Through-hardening stainless steel	High resistance to corrosion. Suitable for mirror-finish polish.	1.2083	X42 Cr 13 (AISI 420)	C48 — C53	Cavity and core inserts
Through-hardening hot-work tool steel	Good dimensional stability in heat treatment	1.2344	X40 Cr Mo V-51 (AISI H-13)	C38 — C54	Cavity and core inserts

and are rated for a shorter production life than a steel mold. Some of the latest materials are closing the gap on steel to a limited extent.

Steels too can vary in thermal conductivity. Stainless steels are substantially inferior in this respect to normal alloys and this can prove a major handicap in molds with high thermal requirements. The tables compare the main materials of mold manufacture, and outline the uses of the leading mold steel types.

Polypropylene is normally non-corrosive in contact with all common mold steels, but a few cases of corrosion have been reported, particularly at vents. Provided cavities and cores are produced in an alloy with a chromium content of 10% or more, there should be no difficulty. Polypropylene can itself be affected by copper alloys. These can induce degradation and should not be used in hot runner components that are in direct contact with the melt. However, there should be no difficulty in using copper alloys for cavity and core components because the melt is rapidly cooled on contact. Indeed, it is the high heat extraction demand posed by polypropylene that has the most direct bearing on the choice of mold material. Stainless steels should be avoided, and if there is any difficulty in engineering adequate cooling channels, then high thermal conductivity materials should certainly be used.

14.4.5.2 Cooling

It is a fundamental requirement of the injection mold to extract heat from the molding. With each cycle, the mold acts as a heat exchanger to cool the injected material from melt temperature to at least ejection temperature. The efficiency with which this is done has a direct bearing on speed of production. Heat is removed from the injection mold by circulating a fluid coolant through channels cut through the mold plates and particularly through the cavities and cores (Figure 14.32). The coolant is usually water but may be an oil if the mold is to be cooled at temperatures near or above the boiling point of water. Such a mold appears hot in relation to the ambient temperature, but it is still cold compared to the plastics melt. If the mold is to be chilled at low temperatures, it is usual to circulate a mixture of water and ethylene glycol anti-freeze. Occasionally the coolant may be air, but this is an inefficient means of heat transfer and should be regarded as a last resort.

Cooling channels represent a real difficulty in mold design. Core and cavity inserts, ejector pins, fasteners, and other essential mechanical features all act as constraints on the positioning of cooling channels, and all seem to take precedence over cooling. However, uniform and efficient cooling is crucial to the quality and economy of the molding, so channel positioning must take a high priority in mold design.

Cooling channel design is inevitably a compromise between what is thermally ideal, what is physically possible, and what is structurally sound (Figure 14.33). The thermal ideal would be flood cooling over the entire area of the molding, but the pressurized mold cavity would be unsupported, and mechanical details like ejectors could not be accommodated. Support could be provided by interrupting the flood cooling chamber with supporting ribs, but the mold construction is complicated by the need to fabricate and seal the cooling chamber. The reasonable and practical compromise provides the cooling channels in the form of easily machined through bores that may be linked either inside or outside the mold to form a complete cooling circuit.

The correct placement of the channels is important. If they are too widely spaced, the result is a

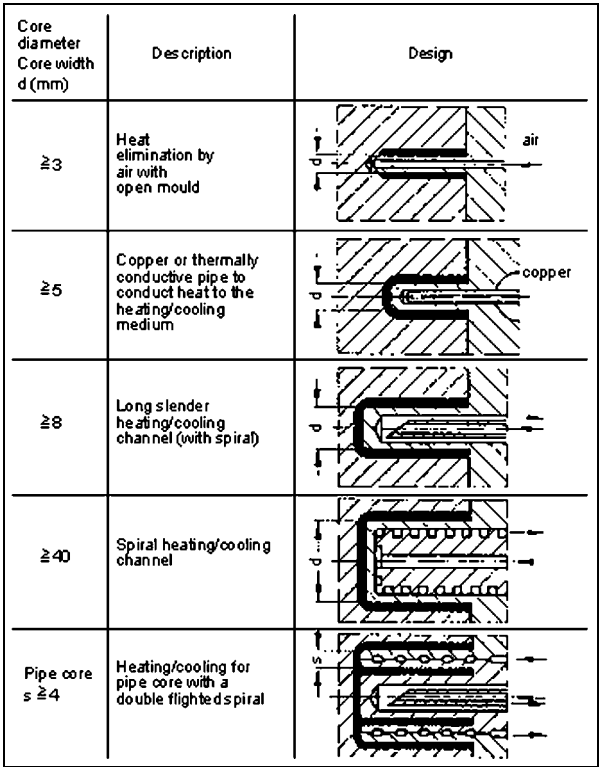


Figure 14.32 Cooling arrangements for cores of various sizes.

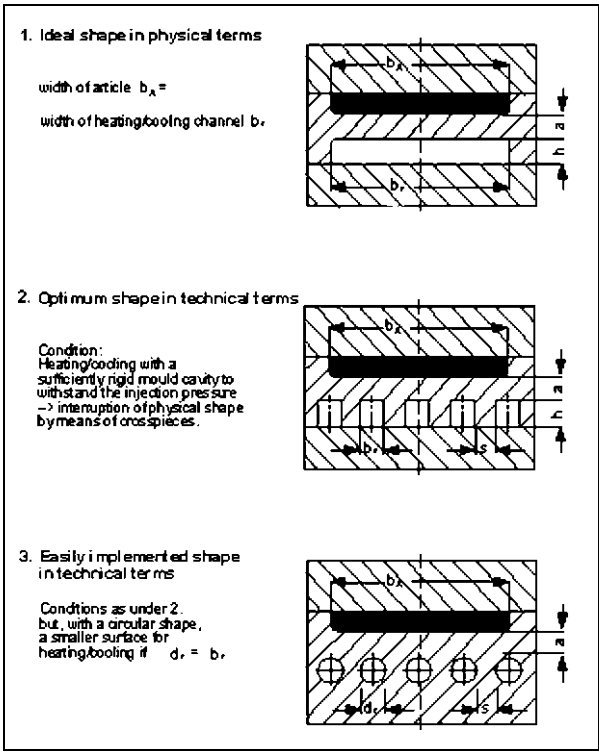


Figure 14.33 Cooling channel considerations.

wide temperature fluctuation over the cavity or core surface (Figure 14.34, Table 14.13). If the channels are too closely spaced or too close to the cavity surface, the mold becomes structurally weak.

Another important consideration in cooling channel design is to ensure that the coolant circulates in turbulent rather than laminar (streamline) flow. The coefficient of heat transfer of the cooling system is drastically reduced in laminar flow. The condition of laminar or turbulent flow is determined by the Reynolds number (Re). This is a di-

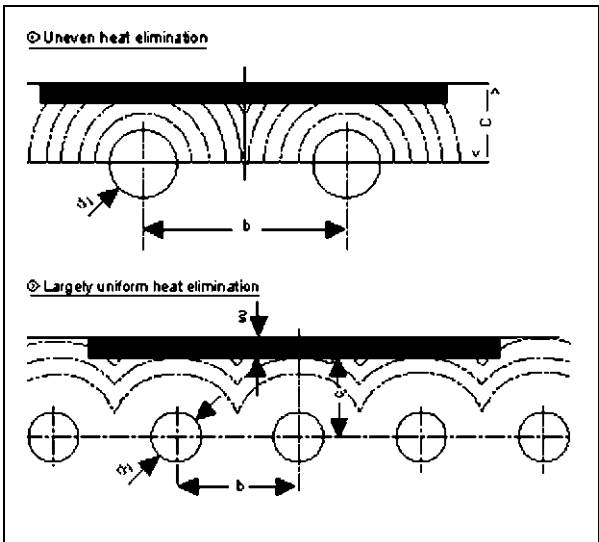


Figure 14.34 Bad and good cooling channel layouts.

mensionless number given by the equation:

$$Re = \frac{Dv\rho}{\eta}$$

where D = channel diameter, v = coolant velocity, ρ = coolant density, and η = coolant viscosity

For a channel of circular cross-section, turbulent flow occurs when the Reynolds number is greater than 2,300. The coefficient of heat transfer of the cooling system continues to increase as turbulence increases, so the design limit of the Reynolds number for cooling channels should be at least 5,000 and preferably 10,000. If the volume flow rate of the coolant remains constant, then the Reynolds number can be increased by reducing the size of the channel. This runs counter to the natural impulse to image that a larger channel must always result in better cooling. It is harder to achieve turbulent flow with oils or anti-freeze solutions because of their greater viscosities compared with water.

Good cooling channel design is particularly important for molds to be used with polypropylene. The material has the highest heat content to remove on cooling of any thermoplastic with the exception of high density polyethylene. This means that slender cores and corners will rapidly and inevitably heat up unless special attention is paid to cooling by means of extensive coolant circulation coupled with the use of heat pipes and high thermal conductivity mold materials. As a general rule, it is impossible to design too much cooling into a polypropylene mold.

14.4.5.3 Venting

When an injection mold fills, the incoming high-velocity melt stream is resisted by and must displace the air in the feed system and cavities. Molders often rely on incidental air gaps between the parting faces and between the assembled parts of the core and cavity to provide a leakage path for air, but this is no substitute for properly engineered venting which should be designed into all molds

Table 14.13 Recommended cooling channel dimensions for polypropylene (refer to Figure 14.34).

Wall thickness w (mm)	Channel diameter d_c (mm)	Channel spacing b (mm)	Channel depth c (mm)
<2	8–10	24–30	20–25
2–4	10–12	30–36	25–30
4–6	12–15	36–45	30–35

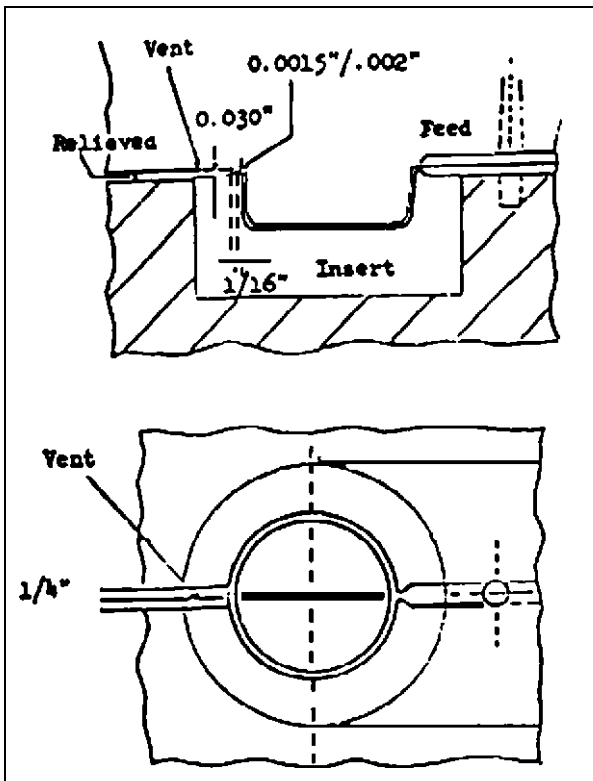


Figure 14.35 Recommended vent dimensions for use with polypropylene.

(Figure 14.35). Provided the vent is machined to the correct depth, the injected material will not flash through the air gap. More than one vent may be used; if necessary up to 60% of the peripheral dimension can be vented. The width of individual vents should not exceed 0.25 in or 6 mm.

Venting can also be used to prevent or minimize gas traps. A gas trap occurs when the flow of injected plastics melt surrounds and isolates an area in the cavity, so trapping air which is rapidly compressed and heated. Burned or charred material is often associated with gas traps. The best remedy is to redesign flow to do away with the gas trap but if this is not possible, venting will help provided the vent is positioned in the correct spot. Most gas traps cannot be vented through the parting faces of the mold. Instead, the vent is machined in inserted pins or plugs. Such vents are prone to blocking unless

one of the parts is in motion. For this reason, an ejector pin is often used for venting. An alternative method is to use an insert of porous steel.

14.4.5.4 Ejection

Ejection is the name given both to the process of removing the molding from the mold and to the means by which it is done. Ejectors inevitably leave witness marks on the molding, and this alone may determine the disposition of the part in the mold. Once that basic choice has been made, there is usually not much further freedom to position ejectors in cosmetically acceptable positions. The choices are much constrained by other features in the mold and the need to put ejectors where they are most needed to overcome the resistance of the molded part.

Ejection may be by means of pins or a stripper plate, or a combination of both. The stripper plate acts on the entire peripheral wall thickness of the part and so distributes the ejection force. This is the preferred method for thin-walled parts, but the method is difficult to apply to anything other than a circular periphery. A variant on this theme is the stripper bar which works on part of the periphery. Most ejection is performed by pins, usually cylindrical in form. Rectangular pins may be used in constricted areas; these are often referred to as blade ejectors. Hollow ejector pins known as sleeve ejectors are commonly used to push the molding off small core pins. Polypropylene is not a very hard or highly rigid material so the rule is to use ejectors that are as large as possible. Ejection of deep-drawn or thin-walled parts is often assisted by an air valve that breaks the vacuum between the molding and the mold core.

References for chapter 14:

1004, 1005, 1012, 1013, 1014, 1016, 1032, 1049, 1057, 1059, 1063, 1106, 1144, 1153, 1154, 1161, 1165, 1170, 1174, 1175, 1179, 1181, 1183, 1184, 1186, 1188, 1196, 1197, 1198, 1200, 1201, 1202, 1205, 1221, 1222, 1223

15 Blow molding

Introduction

Only some 2% of polypropylene is processed by blow molding, and this represents a share of only about 3% of the overall blow molding market (Figure 15.1). On the face of it, this situation is a surprising one. The combination of economy and good properties offered by polypropylene leads to its widespread use in films, fibers, and injection moldings. So, why are the packaging advantages of polypropylene films not exploited in the containers and bottles that the blow molding process produces? Why has the outstanding environmental stress crack performance of polypropylene, and its chemical resistance, not made it the material of choice for blow molding?

The answer lies in the development of blow molding machinery and the differences in melt rheology between polypropylene and polyethylene. Although blow molding of plastics dates from about 1880, rapid developments in machinery and technology only began in the late 1930s, virtually contemporaneously with the introduction of polyethylene. Polypropylene was not commercialized until the mid 1950s, so blow molding technology was largely optimized on the requirements for polyethylene. Blow molding is a relatively low pressure process, using only 1% or less of the pressure levels employed in injection molding. This requires a low melt viscosity, produced by high shear rates and temperatures. The difficulty with polypropylene is that its melt viscosity is far more sensitive to temperature and shear rate than is the case with polyethylene, so there are problems in working polypropylene on polyethylene equipment.

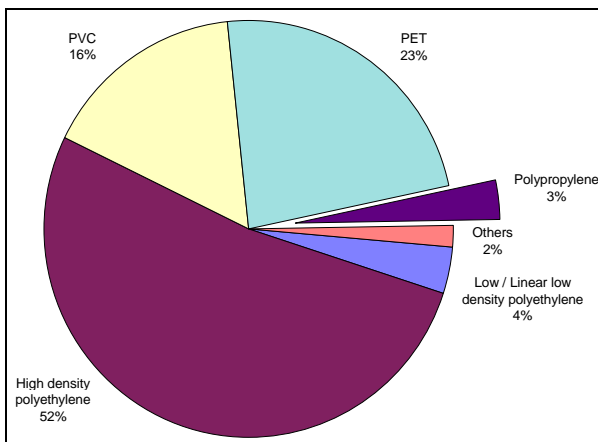


Figure 15.1 Polypropylene share of Western European 1996 blow molding consumption.

Two things are happening to change this. Machinery and technology is now being developed specifically for polypropylene. At the same time, developments in polypropylene are making it a more suitable material for the process. The increased transparency of nucleated, clarified, and random copolymer grades is making them more attractive for bottle and container applications. And advances in polymerization technology have made it possible to produce grades with melt strengths and shear dependencies that are more tolerant of the blow molding process. Consequently, blow molded polypropylene is a growth area. Its market share is currently small, but its growth rate is second only to PET. Polypropylene blow moldings are likely to take market share from PVC and high density polyethylene.

15.1 Blow molding processes

Blow molding is a process for converting thermoplastics into hollow objects. Like injection molding, the process is discontinuous or batchwise in nature, involving a sequence of operations that culminates in the production of a molding. This sequence or cycle is repeated automatically or semi-automatically to produce a stream of molded parts.

The blow molded parts are formed in a mold that defines the external shape only. As the name implies, the inner shape is defined by fluid pressure, normally compressed air. In this respect, blow molding differs radically from many molding processes where both inner and outer forms are determined by mold members. The major advantage is that the inner form is virtually free of constraints because there is no core to extract. The main drawback is that the inner form is only indirectly defined by the mold, so high precision and independent internal features are impossible. This has a bearing on wall thickness which can never attain the consistency and accuracy of a full-mold process such as injection molding.

Blow molding is now a highly developed process with many variant forms (Figure 15.2). At its most basic, the process involves melt processing a thermoplastic into a tube that is generally referred to as a parison. While still in a heated ductile plastic state, the parison is clamped between the halves of a cooled mold, so that the open top and bottom

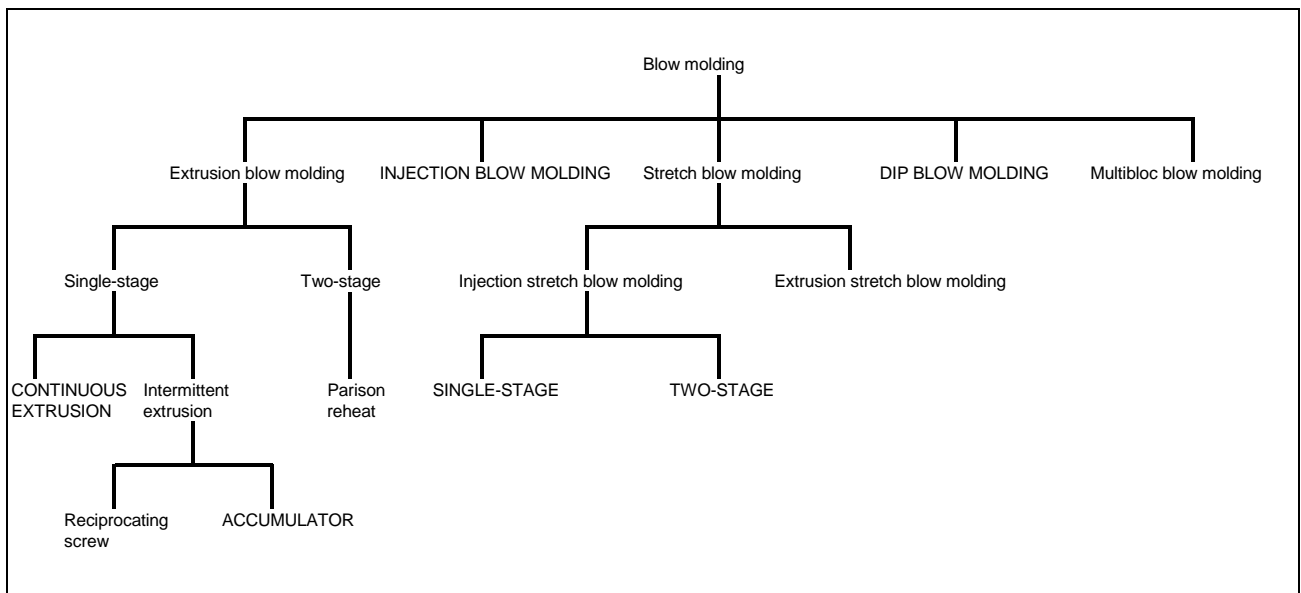


Figure 15.2 Blow molding processes. The processes most frequently used for polypropylene are shown in capitals

ends of the parison are trapped, compressed and sealed by the mold faces. A blowing tube is also trapped in one of the parison ends, creating a channel through which air pressure is introduced within the sealed parison. Air pressure causes the parison to expand like a balloon, so that it takes up the form of the mold cavities. Contact with the cooled mold chills the thermoplastic to its solid state, so the form is retained after the mold is opened and the part removed.

The many variations of the blow molding process are discussed later in this chapter, with an emphasis on those of most importance for processing polypropylene. Two features — the extruder and parison head — are common to many blow molding processes and will be discussed separately.

The leading applications for blow molded polypropylene are:

Foodstuffs

- bottles and containers for mineral water, cooking oils, vinegar, juices, jams, spices, ketchup, mayonnaise, mustard

Household

- bottles and flagons for household chemicals and detergents

Personal care

- bottles for shampoos
- containers for cosmetics

Medical and pharmaceutical

- containers for pills and capsules

Automotive

- expansion tanks

- fluid reservoirs
- ducts
- fenders and trims

Industrial

- tote boxes and trays
- tool boxes

Leisure

- toys
- sports goods

15.1.1 The extruder

Most blow molding processes begin with an extruded tube or parison. The extruder is of the single-screw type and follows the general principles described elsewhere for a polypropylene extruder. The screw should have a length/diameter ratio of 24:1 to 30:1 or more. Screws at the high end of this range are preferable. The compression ratio should be about 3.5:1. A grooved barrel inlet improves extruder efficiency when working with polypropylene. Melt temperatures depend on the type and grade of polypropylene and in particular on the melt flow index. As a rough guide, homopolymers and block copolymers will be processed at about 210°C while the melt temperature for random copolymers should be about 190°C. Melt temperatures greater than 230°C are not normally used in blow molding.

15.1.2 The parison head

The parison head, sometimes called the die head or simply the die, is a specialized form of tubular extrusion die. Its function is to deliver a straight

parison in the correct diameter, length, wall thickness, and at the correct temperature for blow molding. Prior to being clamped in the mold, the parison is suspended unsupported in free air. To avoid undue deformation, it is necessary to extrude the parison vertically downwards. The blow molder extruder is almost always arranged in a horizontal attitude, so the first task for the parison head is to turn the melt flow stream through a right angle. This is difficult to achieve in a way that meets the essential requirement for a constant flow rate at every point in the annular die gap. A second and related requirement is that the parison should carry as little evidence as possible of the weld line formed when the melt stream from the extruder flows around the torpedo. Many parison head designs have been evolved to deal with these problems. The example shown is known as the cardoid type (Figure 15.3). Head design has benefited from computer analysis of the internal flow channels which has removed much of the trial and error and given a greater assurance of success.

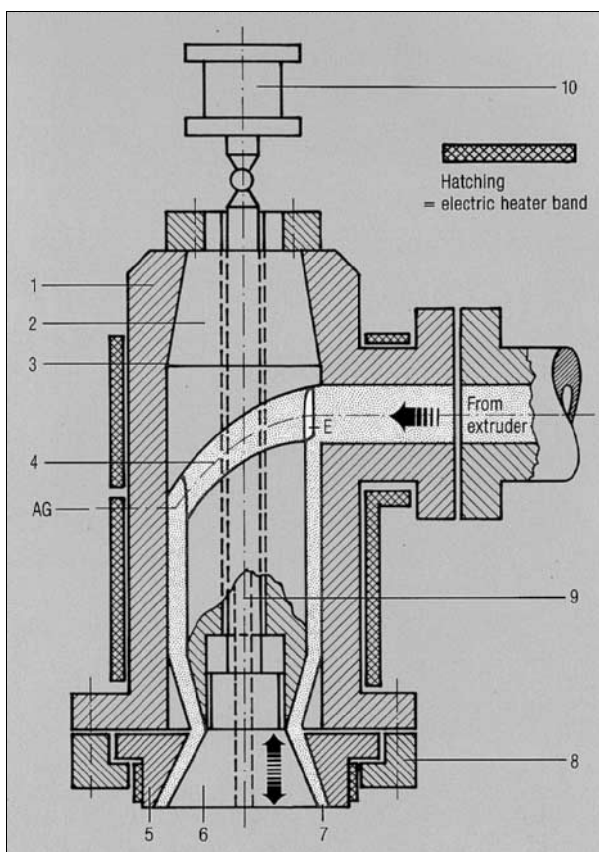


Figure 15.3 Typical parison head. Key: 1 = housing, 2 = torpedo, 3 = seating, 4 = melt flow channel, 5 = die, 6 = mandrel, 7 = die gap, 8 = retainer ring, 9 & 10 = die gap adjustment means, AG = plane of annular flow channel, E = flow divider edge

A further problem is one shared with pipe and tube extrusion dies. This is the difficulty of ensuring that the torpedo and mandrel remain coaxial with the die, without dividing the melt stream with mechanical supports. The example shown uses no supports in the melt stream, relying instead on an accurate seating between the torpedo and the housing. The parts need to be relatively massive for this design to be sufficiently rigid. Smaller torpedoes will need supports in the melt stream and here the challenge is to minimize the formation of weld lines in the parison. Such supports include spider legs, staggered spider legs, breaker plates, screen tubes, and spiral mandrels. The problem is a difficult one and in the worst case, the weld lines show up as local variations in the parison wall thickness.

The basic parison is a tube which in principle at least has a constant wall thickness at all points around its circumference and along its length. In practice, circumferential thickness may vary as a result of weld lines, or if the mandrel is not truly coaxial with the die. Thickness along the parison length may vary due to tensile thinning caused by the weight of the dependent parison. However, the ideal parison with a constant wall thickness is not necessarily the optimum for blow molding. Even simple molded shapes encompass considerable variations in profile. For example, the body of a bottle is much greater in diameter than the neck. For some containers, there may be several significant variations along the axis, and the effect is usually pronounced in technical blow moldings. If such articles are blow molded from a parison of constant wall thickness, then the finished molding will be thinner where the parison has to expand the most and thicker where it has expanded the least. In most cases, the ideal is a finished product with a constant wall thickness at all points. To approach this ideal, what is needed is a parison in which the wall thickness varies along the length so that it is thickest where it must expand the most. This is achieved by parison programming or profiling.

The usual way to do this is by moving the mandrel in an axial direction relative to the die (Figure 15.4). If both die and mandrel are provided with conical outlet features, this movement will increase or decrease the annular die gap between the two. The mandrel movements are controlled by a servo system acting on a pre-programmed thickness profile. The system may include a feedback loop to adjust parison profiling in response to screw speed variations in the extruder.

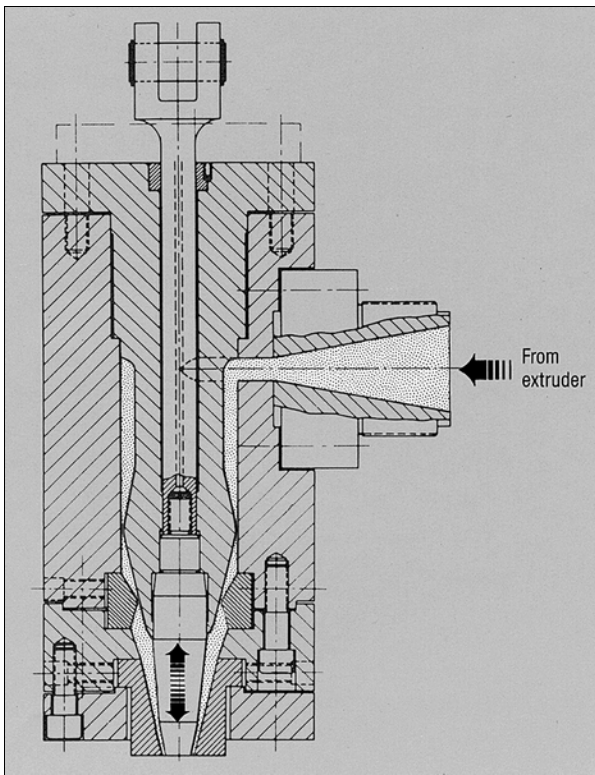


Figure 15.4 Principle of parison wall thickness control by axial movement of the mandrel.

For polypropylene, the die land length in fixed or non-profiling die heads should be about 10:1. The concept is difficult to apply to the conical melt flow passage in variable die heads, but it can be taken to mean those zones in which melt passage thickness is substantially the same as the die outlet gap. Parison head temperatures should be in the region of 190°C to 200°C for polypropylene homopolymers and block copolymers and about 170°C to 180°C for random copolymers.

15.1.3 Extrusion blow molding

In extrusion blow molding, an extruder feeding a parison head is used to produce a parison as a precursor or preform for the molding process. The configuration of individual machines may vary greatly but some essential elements can be distinguished (Figure 15.5). The extruder and parison head are arranged to extrude a parison vertically between the two halves of a blow mold. The mold halves are clamped to platens that are linked to a mold closing and clamping device. A blow pin is provided to inject air under pressure into the parison. Because blow molding is conducted at relatively low pressures, the construction of the machine and mold can be much lighter than is required for injection molding. Consequently, machines, and particularly

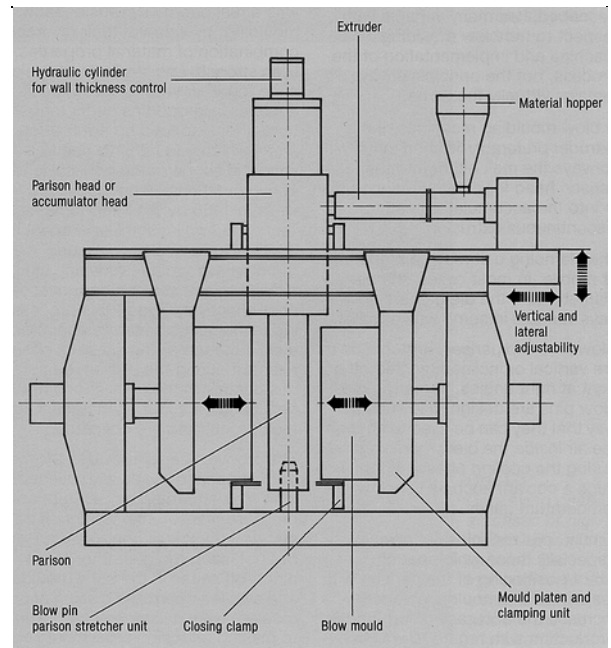


Figure 15.5 Typical extrusion blow molding machine.

molds, are much cheaper than those used in injection molding. Machine production rates can be increased by using multiple molds or multi-cavity molds with multiple parisons.

These general principles apply to a number of distinct extrusion blow molding processes which are described in the following sections of this chapter.

15.1.3.1 Single-stage

Single-stage extrusion blow molding produces a blown article in a single integrated process cycle. Blow molding immediately follows parison extrusion and relies on the melt condition of the parison for the deformation and flow necessary to take up the shape of the mold. There is no reheating of the parison before molding. The principal variants are the continuous extrusion and the intermittent extrusion processes. Extrusion in this distinguishing sense applies to extrusion of the parison rather than the operation of the extruder.

15.1.3.2 Continuous extrusion

The continuous extrusion blow molding process is the most widely used for working with polypropylene. In this process, the parison is extruded continuously from the parison head, between the open mold halves (Figure 15.6). When the required length of parison has been produced, the mold is closed, trapping the parison which is severed by a hot knife. Land or pinch-off areas on the mold compress and seal the upper and lower ends

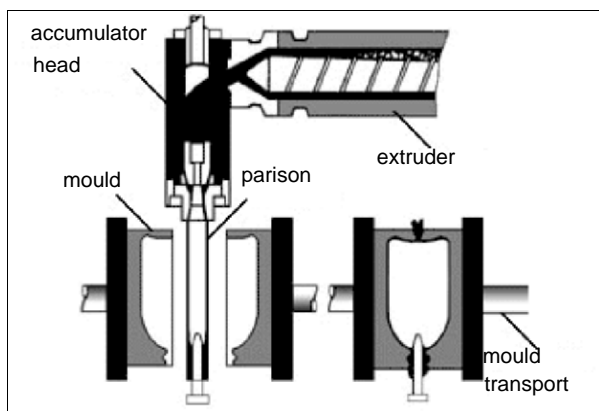


Figure 15.6 Basic extrusion blow molding process.

of the parison to make an elastic air-tight object. Compressed air is introduced through the blow pin into the interior of the sealed parison which expands to take up the shape of the mold cavities. The cooled mold chills the blown object which can then be ejected when the mold opens.

The blowing air can be introduced in a variety of ways. In the simplest case, the parison is extruded downwards so that the open end slips over a blow pin. Alternatively, the blow pin can be introduced from above the mold after the parison is severed, or blow needles can be built into the mold, where they pierce the parison as the mold closes.

Relative movement between the parison head and mold is necessary so that parison extrusion can proceed continuously while the mold is closed. This is achieved in many different ways. The mold may be lowered, moved aside laterally, or swung aside on an accurate path. Alternatively, the extruder may be moved whilst the mold remains stationary. Often, two molds are used in a shuttle arrangement, so that one is open for parison extrusion while the other is performing the blowing cycle. One method of mold movement results in very high production rates. In such machines, generally known as wheel machines, a number of molds are mounted on a rotary table. Movement of the table carries the closed mold away and presents a new open mold to the diehead, so allowing extrusion to continue.

Except in special cases such as the shuttle and wheel machines, the extrusion rate of the parison must be synchronized with the blow cycle for a single mold. This may involve a relatively slow extrusion rate, running the risk of thinning as the parison stretches under its own weight. For this reason, continuous extrusion blow molding is best suited to thermoplastics with a high melt viscosity or high

melt strength or to short or thin-wall parisons. The upper limit for working with polypropylene is a container with a capacity of about 10 liters.

15.1.3.3 Intermittent extrusion

In intermittent extrusion blow molding, the parison is extruded from the parison head discontinuously. When a parison of the required length has been produced, extrusion is interrupted until the next parison is required for the subsequent blowing cycle. This makes it unnecessary to have relative movement between the die and mold. The process is generally used to make larger blow moldings like drums or automotive fuel tanks. These articles require large and heavy parisons which, when extruded normally, sag and thin down under their own weight. Intermittent rapid extrusion reduces this tendency, and it is achieved either by reciprocating screw or accumulator means.

Intermittent extrusion blow molding is best suited to long or heavy parisons and to thermoplastics with a low melt viscosity or low melt strength.

Reciprocating screw

Reciprocating screw intermittent extrusion blow molding machines use an extruder unit in which the screw is capable of axial as well as rotational movement. The function is virtually identical to that of the injection unit on an injection molding machine, except that the blow molding unit functions with a lower melt pressure and flow rate. The parison is prepared in two steps:

In the melt preparation phase, the screw rotates, so heating and melting the material which is conveyed along the screw flights to the forward end of the screw. The extruder die block is closed by a valve, so the accumulating melt forces the still-rotating screw back against a controlled resistance until sufficient melt has accumulated to make the next parison. At this point, screw rotation stops.

In the parison extrusion phase, the extruder die block valve is opened and the screw performs the action of a ram by moving forward in the axial direction without rotating. This forces the accumulated melt at the forward end of the screw through the parison head, where it is extruded at a relatively high flow rate. In practice, the flow rate is limited by the onset of shear phenomena such as sharkskin and melt fracture. Polypropylene is shear sensitive so high extrusion rates may result in a parison with a low melt viscosity.

Accumulator

Intermittent accumulator extrusion blow molding machines use a normal axially-fixed continuously operating extruder to prepare the melt. The accumulator is a heated reservoir where the melt is temporarily stored in the intervals between parison extrusion. The parison is extruded by a ram acting on the stored melt. This means that the melt volume in the accumulator fluctuates in a cyclic manner. It is substantially empty immediately after the parison is extruded, then it gradually increases during the blowing phase, reaching a maximum immediately before extrusion. Accumulators introduce a number of problems. They increase the heat history of the melt, and they involve valves and complex flow paths that offer flow resistance and may also lead to difficulties with cleaning and even degradation. Accumulators should be designed on the FIFO principle; the first material in must be the first out.

Blow molding accumulators take one of two forms. The separate accumulator is a heated chamber which is an integral part of the blow molding machine. The capacity of such a chamber can be very large and can if necessary be served by several extruders. The other type of accumulator is built

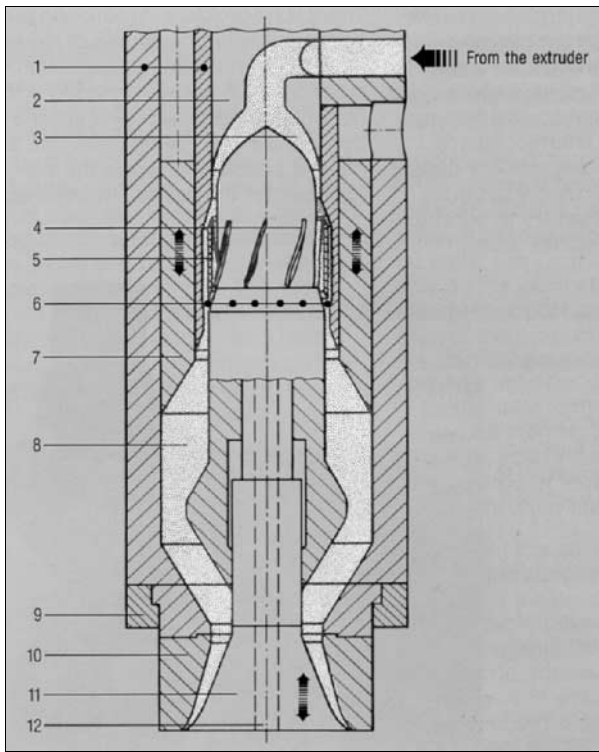


Figure 15.7 Example of accumulator parison head by Bekum. Key: 1 = housing, 2 = torpedo, 3 = cardoid groove, 4 = guide legs, 5 = guide ring, 6 = merging zone, 7 = annular ram 8 = accumulator melt chamber, 9 = die retainer ring, 10 = die, 11 = axially adjustable mandrel, 12 = axial bore

into the parison head (Figure 15.7). This takes the form of an annular ram that surrounds the mandrel and torpedo. The construction of the parison head becomes quite complicated and there is the potential for melt leakage and degradation between the moving parts, so design and engineering must be of a high standard. FIFO principles are difficult to apply. The shot volume available from an accumulator parison head is limited by practical considerations of head size and construction.

15.1.3.4 Two-stage

Two-stage extrusion blow molding treats the parison as a true preform by separating the functions of parison preparation and blow molding. Parisons are produced by conventional tube extrusion methods. The tube is cooled and cut into parison lengths that are stored before being reheated and blow molded in the normal way. The reheating process can be selective, leading to a degree of control over wall thickness in the blown article. The reheating process also tends to relax stress in the parison, resulting in a stronger product. However, the process has a number of disadvantages. The polymer heat history is increased by the use of two heating cycles, energy use is increased, and costs arise from the storage and handling of parisons. The process is not suited to high production speeds and is little used.

15.1.4 Injection blow molding

The injection blow molding process uses injection molding rather than extrusion to produce the precursor; it is generally known as a preform rather than a parison. The injection blow molding machine has an integral injection unit and a multi-impression mold assembly in which the mold cores are mounted on a rotary table. The cores double as blowing pins and index in 120° steps between injection, blowing and ejection stations (Figure 15.8). Station one is the preform injection mold where the preform is formed over the core pin. The preform

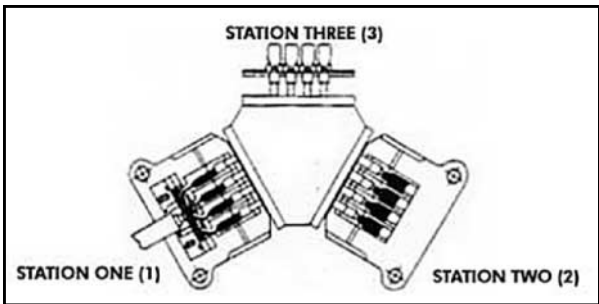


Figure 15.8 Injection blow molding stations.

has a hemispherical closed end. The other end is an open bore, formed by the core pin. External details, such as the thread and neck flange for a screw-top container, are directly produced by injection molding. While the preform is still hot and plastic, the injection mold is opened and the preforms, still on the core pins, are rotated to station two, the blowing station. Here the preforms are enclosed within the blow mold, and the blow molding is produced by introducing blowing air through the core pins. The blow mold is then opened, and the finished articles, still on the core pins, are rotated to an ejection station where they are stripped off. The machine has three sets of core pins, so that the three stages take place simultaneously.

The injection blow molding process has a number of advantages. The preform can be injection molded in a profiled shape that corresponds to the requirements of the blow mold form. The neck form is molded in its entirety at the injection stage, resulting in a quality and precision that is superior to a blow molded neck. There is no pinch-off scrap to be removed and recycled and no bottom seam. There are some drawbacks too. The process is difficult to use with high melt viscosity materials. Integral handles, view stripes, and multi-wall constructions are all impractical.

Process conditions are rather different from those used in extrusion blow molding. For polypropylene, injection melt temperatures range from 230°C to 245°C. The process is best suited to smaller containers ranging in capacity from 1 mL to about 1.5 liters, typically for medical, pharmaceutical, and personal care applications.

15.1.5 Stretch blow molding

Stretch blow molding processes are designed to produce biaxial orientation in the blown article. Conventional blow molding imparts a degree of circumferential orientation, caused by the expansion of the parison into the mold cavity, but there is little or no axial expansion and correspondingly, no axial orientation. Stretch blow molding provides for axial orientation by stretching the preform axially before or during blowing. This is normally accomplished by means of a stretch rod that is advanced axially inside the preform at a controlled rate. These processes are in widespread use for producing polyethylene terephthalate (PET) carbonated drink bottles and are also used to a lesser extent with PVC. Stretch blow technology is now being adapted and developed for use

with polypropylene, and this is an important growth area in blow molding. Compared to conventionally blown polypropylene containers, the oriented stretch blow type are characterized by better transparency and gloss, increased resistance to burst pressure, and reduced permeability. The improved rigidity of oriented polypropylene (OPP) means that containers can be made lighter and cheaper, and the improved strength may result in savings on additives such as impact modifiers. Specially developed nucleated or clarified random copolymer grades produce a blown bottle of glass-like transparency. The disadvantages are that the process is more critical and complicated than conventional blow molding, and the capital cost of equipment is high. Stretch blow processes cannot produce containers with integral handles.

Stretch blow molded polypropylene containers have some important advantages. They can be sterilized at higher temperatures than competitive containers, and are not prone to environmental stress cracking. OPP containers can be hot filled at about 90°C compared to a limit of about 60°C for the PET equivalent. The lighter weight of OPP containers results in reduced transport and warehousing costs. Applications include containers for pharmaceutical, healthcare, personal care, household chemical, and food products. A major opportunity, particularly in Europe, is the non-carbonated water bottle market currently served by PVC.

Stretch blow molding may be performed by injection or extrusion means.

15.1.5.1 Injection stretch blow molding

Injection stretch blow molding processes use hollow preforms produced by injection molding. The preform is short and thick-walled relative to the finished blown article. The neck profile complete with screw thread is entirely formed by injection molding and is not modified by the blowing process. The other end of the preform is closed and typically dome shaped.

The design and precision of the preform has a critical influence on the degree of orientation and quality of the blown article. Polypropylene preforms will typically have a minimum wall thickness of 3.0 mm and may be as thick as 6 mm. The actual wall thickness and any profiling will depend of course on the shape and size of the blown container. Like other preform processes, the finished blown article is free of seams, flash, and pinch-off scrap and is characterized by precise neck dimen-

sions. The injection molded preform may be converted to a blow molding either by the single-stage or the two-stage process. Both are used in the processing of polypropylene.

Single-stage

In the single-stage injection stretch blow molding process, the preform injection molding step is integrated with the stretch blow machinery. The machines are generally arranged for rotary operation, so that the preforms pass directly from the injection molding station to a thermal conditioning station and thence to a stretch blow molding station (Figure 15.9). The process can be used to produce wide-mouthed jars as well as necked bottles, but it is less suitable for high speed production than the two-stage process.

The injection molded preform is cooled rapidly in the mold to about 90°C (Figure 15.10) and the core pin is extracted as soon as the surface skin has cooled sufficiently to make the preform physically stable. The pin has a generous draft angle to make this easier. Single-stage stretch blow preforms commonly have a wall thickness of 3mm to 4mm.

The thermal conditioning process is the most critical part of the operation. The optimum stretch blow temperature span for polypropylene is very narrow, ranging from about 145°C to 155°C. Uniform heating of the order of $\pm 1^\circ\text{C}$ is important;

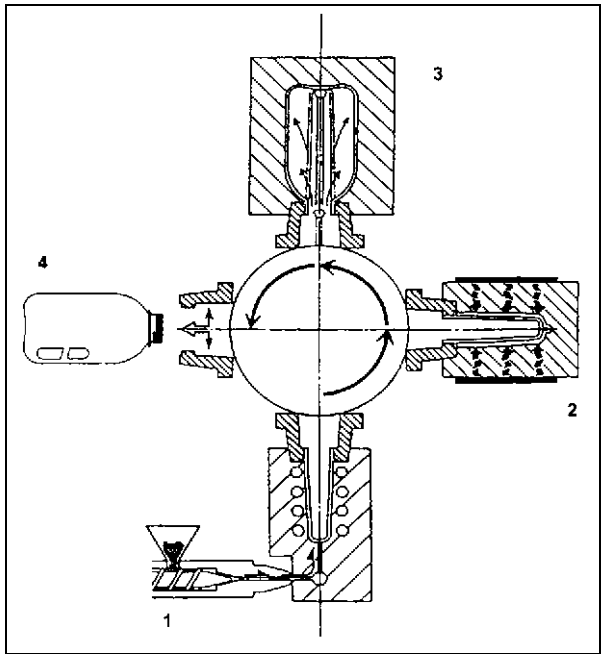


Figure 15.9 Single-stage injection stretch blow process. Key: 1 = preform injection molding station, 2 = thermal conditioning station, 3 = stretch blow molding station, 4 = ejection station

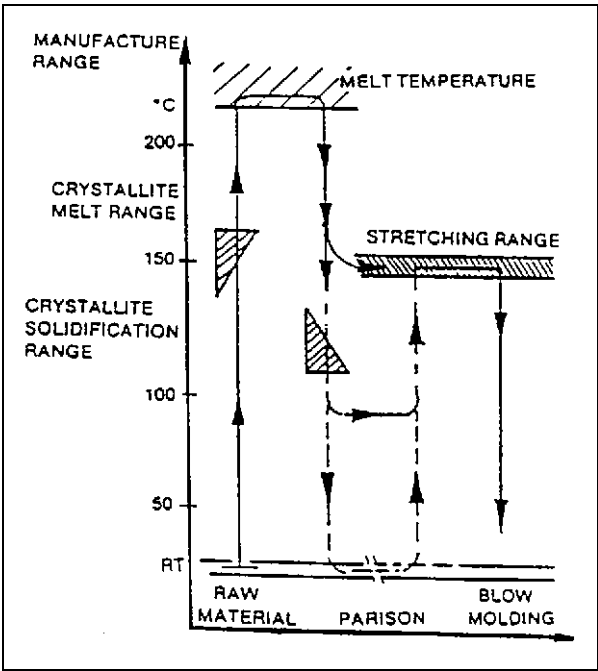


Figure 15.10 Temperature range for stretch blow molding polypropylene. [1122]

thermal conditioning stations include up to 36 independently controlled heat zones, typically using a combination of infrared radiant external heaters and hot air for internal heating.

The thermally conditioned preform is transferred to a blow mold and stretched and oriented axially by an internal stretch rod, either immediately prior to, or simultaneously with the blowing operation that provides radial stretch and orientation. Blowing pressures range up to about 40 bar. The blow mold temperature is relatively high at 35°C to 65°C in order to minimize strain in the bottle. For a given bottle size, the degree of orientation is determined principally by the parison length and diameter. For polypropylene, stretch ratios are relatively high. In the wall thickness of the bottle body, the figure may be as high as 15:1. Axial stretch is about 2:1 to 4:1; diametrical stretch ranges from 2.5: to 3.5:1

Two-stage

The two-stage or re-heat injection stretch blow molding process completely separates the preform injection molding operation from the blow molding operation. Indeed, the two operations may be carried out in different locations by different manufacturers, with a substantial time interval between them. The process lends itself to high rates of production and also has the advantage that preform production may be entrusted to a specialist processor. On the other

hand, the process involves two heating operations, resulting in a greater energy use and increased heat history in the polymer. Another disadvantage is the need to store and handle preforms.

Before being blown, the preforms must be reheated from room temperature and are then thermally conditioned and stretch blown in a similar manner to the single-stage process. The two-stage or reheat stretch blow machine is usually arranged for rotary high speed continuous operation.

15.1.5.2 Extrusion stretch blow molding

Extrusion stretch blow molding is a two-stage process using two mold/mandrel sets — one for pre-blow and the other for final blow. An extruded parison is first pinched off and blown conventionally in a relatively small pre-blow mold to produce a closed-end preform. The preform is then transferred to the final blow mold where an extending stretch rod within the blowing mandrel bears on the closed preform end to stretch it axially. The stretched preform is then blown to impart circumferential stretch. Standard blow molding machines can be converted for extrusion stretch blow molding. The process is most often used for PVC bottles.

15.1.6 Dip blow molding

The dip blow molding process bears some resemblance to injection blow molding in that it is a single-stage process performed with a preform on a core/blow pin (Figure 15.11). The difference is in the way the preform is made. The process uses an accumulator cylinder which is fed by an extruder. The cylinder has an injection ram at one end while

the other is a free fit over the blow pin. The blow pin is plunged into the melt so that a neck mold on the pin seals the end of the accumulator cylinder. The injection ram is advanced to fill the neck mold; then the blow pin is withdrawn at a controlled rate so that it is coated with a melt layer extruded through the annular gap between the pin and the accumulator cylinder. The thickness of the coating can be varied or profiled to an extent by varying the speed of the blow pin and the pressure on the injection ram. After trimming, the preform is blow molded in the same manner used for injection blow molding.

The process results in a seam and flash free container with a high quality molded neck. The preform is produced at a lower pressure than that used for injection molding, so the machine can be more lightly and cheaply constructed and the preform is formed under relatively low stress. Like injection blow molding, the process is best suited to the production of smaller containers.

15.1.7 Multibloc blow molding

The multibloc process is used for high volume blow molding of very small containers such as pharmaceutical vials. A multi-cavity mold is used with an extruded parison whose circumference approaches twice the total width of the closely spaced cavities. Before the mold closes, the parison is stretched and semi-flattened laterally so that it extends across the full width of the cavities (Figure 15.12). The process is usually combined with blow/fill/seal techniques.

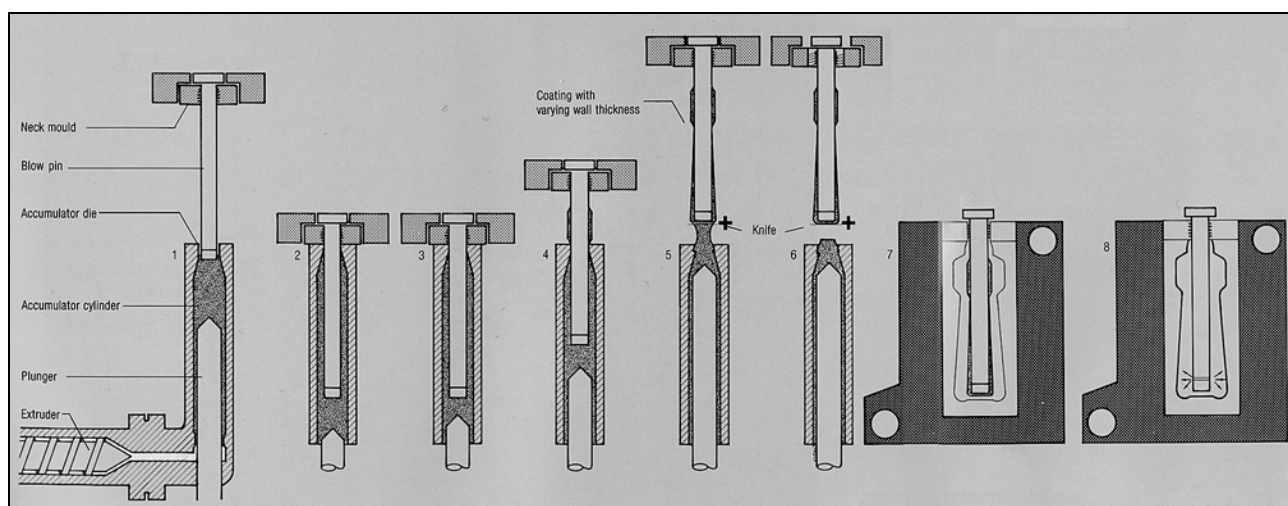


Figure 15.11 Stages in the dip blow molding process. Key: 1 = accumulator filled, 2 = blow pin inserted, 3 = neck mold filled, 4 = blow pin partially withdrawn, 5 = blow pin fully withdrawn at variable speed, 6 = preform trimmed, 7 = preform clamped in mold, 8 = preform blow molded

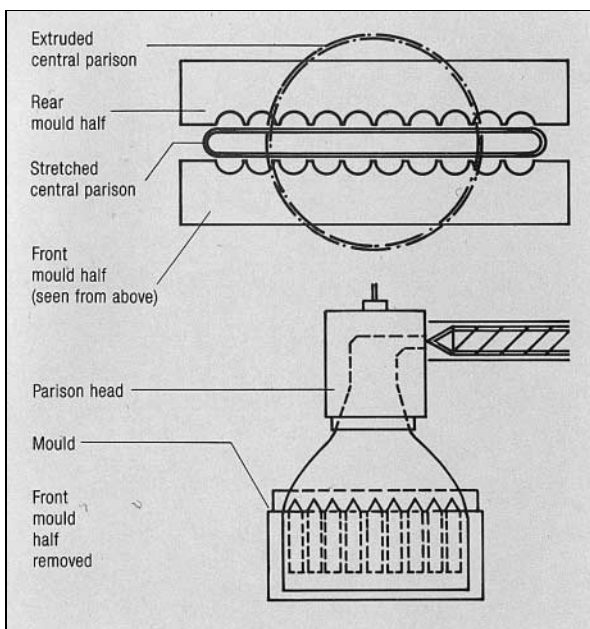


Figure 15.12 Multibloc process.

15.1.8 Other blow molding techniques

15.1.8.1 Coextrusion

Just as in the production of film, coextrusion is now an essential technique in the production of high performance blow molded containers. The parison is coextruded with a number of different layers, each of which contributes an important property to the finished package. Increasingly, a mid layer may consist of recycled material which is encapsulated between inner and outer layers of virgin polymer.

Coextruded blow moldings commonly include from two to six layers, although more can be accommodated if necessary. The construction usually includes one or more barrier layers. These are polymers with a particular resistance to the transmission of water vapor or gases such as oxygen or carbon dioxide. Examples are polyamides, polyvinylidene chloride (PVDC), and ethylene vinyl alcohol (EVOH). Their presence greatly enhances the performance of the blow molding as a package for foodstuffs and other critical products. The barrier materials are all deficient in some respect — price, mechanical strength, moisture resistance — as a material of sole construction for a blow molding, hence their deployment in thin layers shielded by other more robust and economical body plastics.

Two considerations lead to a high layer count in coextruded blow molded products. The barrier materials are incompatible with body materials such as polyethylene and polypropylene, so intermediate layers of a mutually compatible adhesive must be included to bring about a bond between

the layers. And some barrier layers are so deficient in other respects that they themselves need protective layers before they can be deployed effectively. Ethylene vinyl alcohol has outstanding resistance to oxygen transmission but has high rates of moisture absorption and water vapor transmission, both of which damage its oxygen barrier performance. The material needs both protective layers and adhesive layers, so contributing five layers whenever it is used. The adhesive layers are usually known as tie layers; one example used with ethylene vinyl alcohol is an ethylene-vinyl acetate-maleic anhydride terpolymer. A typical coextruded polypropylene bottle will include body, regrind, barrier and tie layers (Figure 15.13).

Such a container is produced by performing conventional blow molding operations on a coextruded multilayer parison. A coextrusion parison head, served by a separate extruder for each distinct component material, is used to produce the parison. The barrier and tie layers are usually very thin, so the flow engineering in the head is critical in order to preserve the integrity of the layers. For this reason, the various melt streams are merged as close to the die exit as possible, even though this complicates die head construction (Figure 15.14). Other disturbing influences, such as parison profiling and intermittent extrusion, are often avoided. If parison profiling is required, the mechanical complication of the parison head is such that this is usually accomplished by axial movement of the die rather than the mandrel.

15.1.8.2 Sequential extrusion

Sequential extrusion blow molding is a special multi-material technique used for the production

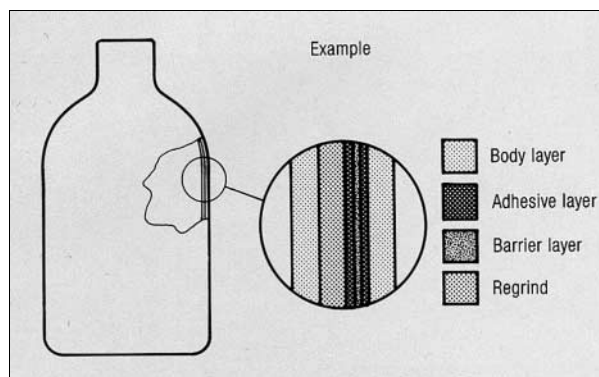


Figure 15.13 Typical 6-layer coextruded blow molded bottle. Key: 1 = inner body layer of polypropylene, 2 = regrind material, 3 = tie layer, 4 = ethylene vinyl alcohol barrier layer, 5 = tie layer, 6 = outer body layer of polypropylene

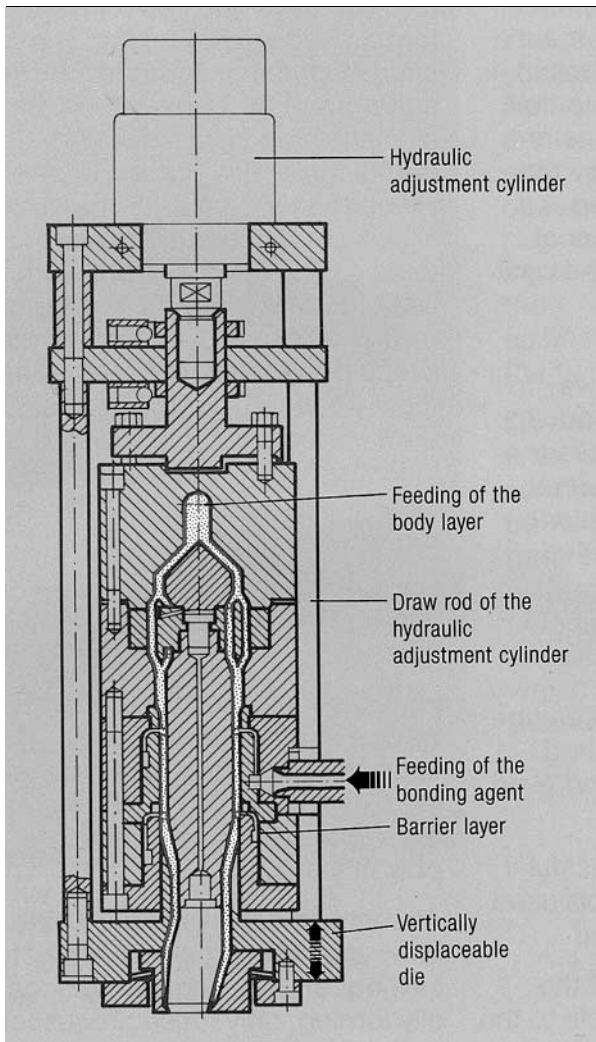


Figure 15.14 Three-layer coextrusion parison head with die profiling.

of technical articles. The different materials are chosen typically to contribute complementary mechanical properties and are present in distinct sequential zones in the finished part. Normally two materials are used but three or more are possible. The die-head is served by separate external ram accumulators for each material. These are operated sequentially, typically in A-B-A sequence, to produce a parison with three distinct material zones in axial succession. The parison is subsequently blow molded by normal techniques.

A typical application for sequentially blow molded polypropylene is an automotive air duct in which rigid end sections are joined by a central flexible zone (Figure 15.15). The flexible zone allows for installation mismatches, accommo-

dates thermal expansion, and damps vibration noise. The rigid portions allow for direct connection to other mechanical elements in the assembly.

15.1.8.3 Blow/fill/seal

The blow/fill/seal process is a complete packaging technique that integrates the blow molding and container filling steps. This provides for aseptic filling of the hot as-blown container and is used for pharmaceutical, food, and cosmetic products. The process employs a two-part mold in which the container body mold cavity blocks are separate from the neck-forming members (Figure 15.16). The body mold closes on the parison which is blown normally by a neck calibrating blow pin. Immediately, with the mold still closed, the liquid contents are injected through the pin. The pin is then withdrawn and the neck is formed and sealed under vacuum by the neck-forming members. Both mold parts then open to eject a filled and sealed container. Small containers may be formed entirely by vacuum rather than blowing.

Blow/fill/seal machines are specially adapted for clean and sterile working. The parison knife runs at temperatures up to 400°C to ensure a sterile cut. Blowing air is generated by an oil-free compressor and is filtered down to 0.2 micron in sterile filters. The filling region of the machine is swept by sterile air, and the entire machine is housed in clean room conditions. The normal melt temperature for extrusion is sufficient to produce a sterile parison. Complete blow/fill/seal cycle times typically range from 9 to 20 seconds. Polypropylene is a leading material for blow/fill/seal applications, generally in the form of high-purity food approved and other

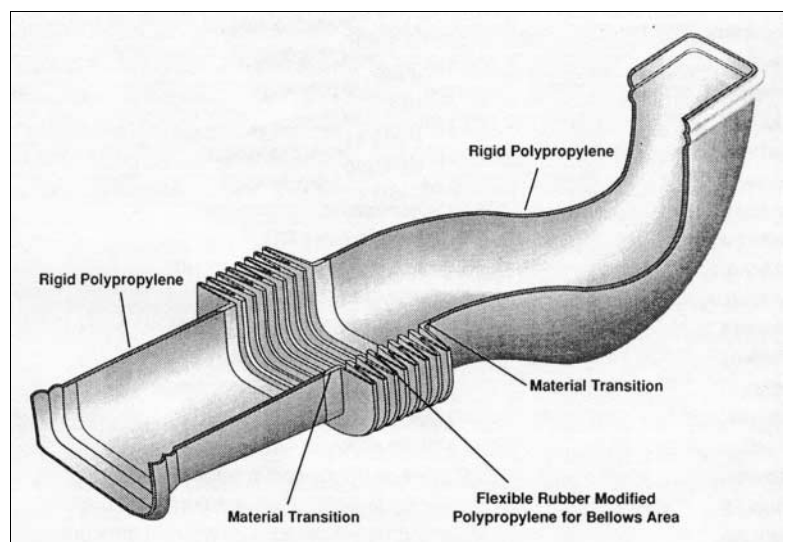


Figure 15.15 Article produced by sequential extrusion blow molding.

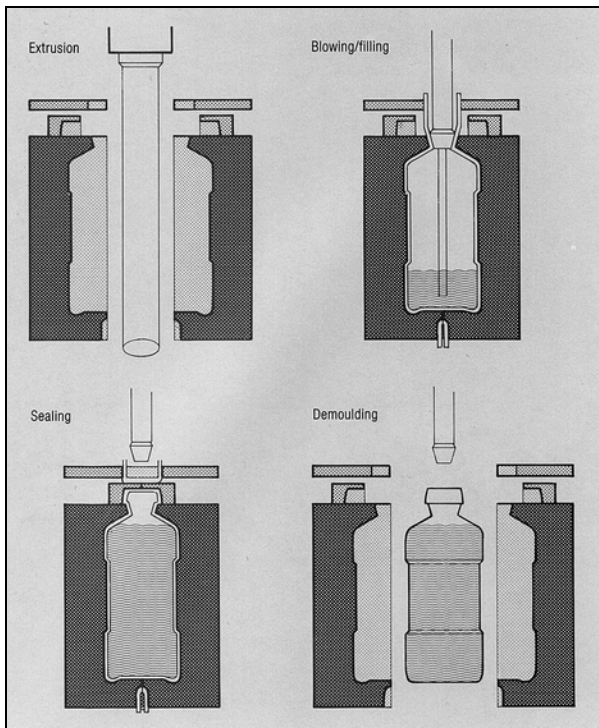


Figure 15.16 Stages in the blow/fill/seal process.

grades free of potentially harmful additives.

15.1.8.4 3D blow molding

Because blow molding is performed on a cylindrical parison, the process is not well suited to the production of technical articles with complex forms that deviate substantially from the parison axis. Such forms can be produced by conventional blow molding, but only by using a large parison that in its flattened form blankets the complex mold cavity. The penalty for this is the formation of an excessive amount of pinch-off scrap.

Recent developments in parison handling equipment and in blow mold design now make it possible to manipulate a relatively small parison

into the complex mold cavity. The result is a blow molding largely free of flash and scrap and offering considerable process savings. There are many such techniques, some of them proprietary property, and they are collectively known as 3D blow molding.

15.2 Blow molds

Essentially, the blow mold consists of two halves, each containing cavities which, when the mold is closed, define the exterior shape of the blow molding. Because the process produces a hollow article, there are no cores to define the inner shape. The blow molding process is carried out at relatively low pressures, so blow molds can be more lightly engineered than injection molds and are correspondingly cheaper and quicker to manufacture. Single cavity molds are used when working with a single parison. When multiple parisons are in use, a number of single cavity molds may be mounted on the machine platen, or the requirement may be met by a multiple cavity mold. Mold details will vary considerably according to the geometry of the product and the blow molding process in use. To illustrate the principles, we will consider the simple case of a single cavity extrusion blow mold for a bottle (Figure 15.18).

15.2.1 Basic features

The mold consists of two halves that meet on a plane known as the parting line. The plane is chosen so that neither cavity half presents an undercut in the direction of mold opening. For most bottle designs, this requirement presents little or no difficulty. For articles of asymmetrical cross-section, the parting line is placed in the direction of the greater dimension. The two mold halves are aligned by guide pillars and bushes to ensure that

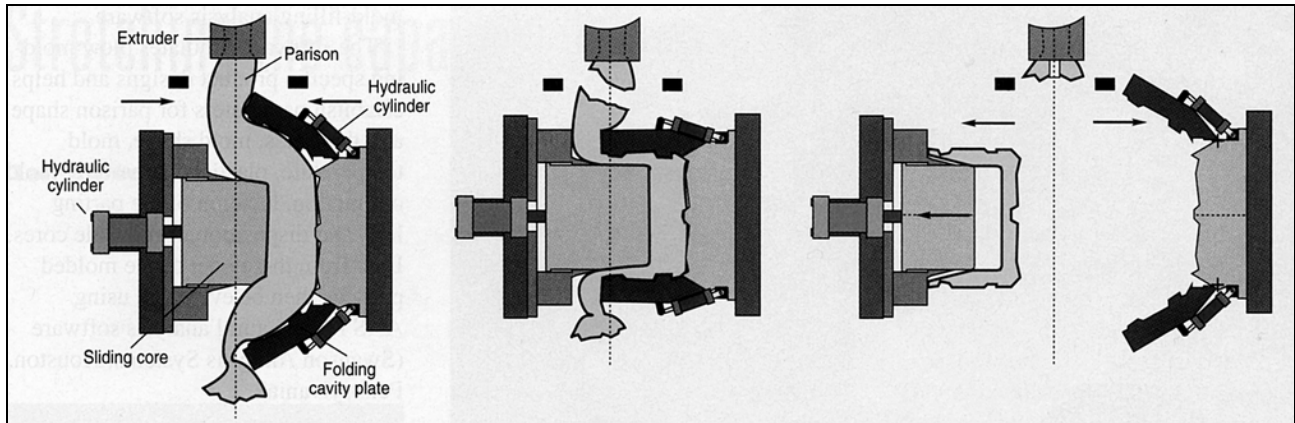


Figure 15.17 Placo process for 3D blow molding. . Key: A = mold begins to close on pre-pinched and pre-blown parison, B = mold fully closed with core forward and side walls hinged in, C = mold open and core retracted

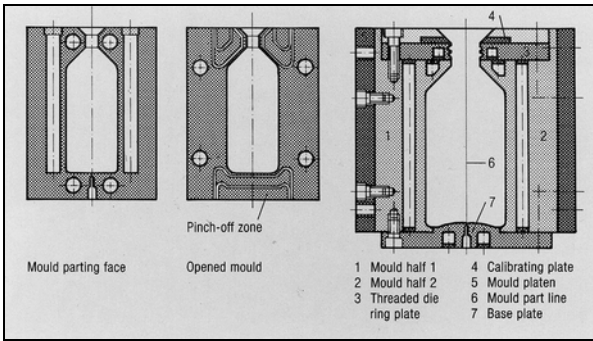


Figure 15.18 Principal features of an extrusion blow mold.

there is no mismatch between the cavities. The parison passes across the mold in the axis of the cavity and is pinched and compressed between the faces of the closing mold at the neck and base regions of the cavity. These are known as the pinch-off zones. The base and neck regions of the mold are typically formed by separate inserted mold blocks. The mold includes channels for the circulation of cooling water.

15.2.2 Materials of construction

The key factors influencing the choice of materials for a blow mold are durability, thermal conductivity, finished cost, and surface finish. The main cavity body for polypropylene blow molds is usually produced in machined aluminum alloy or a cast zinc or other non-ferrous alloy. For long production runs, cast beryllium copper may be preferred. The pinch-off zones are subject to compressive stress and wear and these are usually furnished as inserts of alloy steel or hard beryllium copper.

15.2.3 Pinch-off zone

The pinch-off zone performs two functions. It must weld the parison to make a closed vessel that will contain blowing air, and it must leave pinched-off waste material in a condition to be removed easily from the blown article. To accomplish this, the pinch-off zone has a three-stage profile, consisting of pinch-off edge, pressing area and flash chamber (Figure 15.19). The pinch-off edge is flush with the mold parting line and forms part of the cavity periphery. The edge should be as narrow as possible depending on the material of construction. Steel edges can be from 0.3 mm to 1.5 mm wide; for softer materials the dimensions should be 0.8 mm to 2.5 mm. The pressing area is recessed into the mold parting face by an amount depending on the parison thickness. Its function is to displace melt into the weld area to ensure a strong weld that is substan-

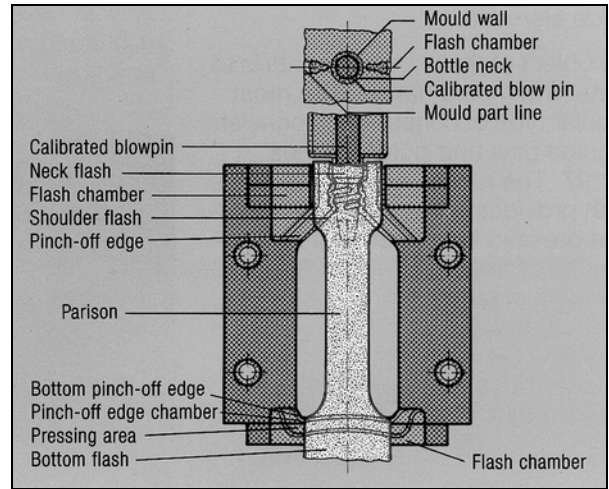


Figure 15.19 Pinch-off zones.

tially equal in thickness to the blown wall thickness at the same point on the parison axis. The pressing area depth is typically determined by trial and error and is often given a ribbed surface to improve cooling of the waste material by increasing the area available for heat transfer. The flash chamber is recessed to a greater depth than the pressing area, typically to about the thickness of the parison. If it is made too deep, heat transfer will suffer and the parison scrap will cool too slowly. Its function is to limit the extent of the pressing area and so limit the force opposing mold closing. The steps between the different levels should be strengthened by angling the riser face by 30° to 45° to the parting face.

15.2.4 Blowing and calibrating devices

The blow pin is the means by which blowing air is inserted into the parison through what will become a hole in the finished blow molding. In the case of a bottle (Figure 15.20), the blow pin is inserted through the neck before or after mold closing. The blow pin body has the secondary function of calibrating the bore of the bottle neck. If the blow pin is plunged into the neck after mold closing, it is possible to produce a flash-free bottle mouth. After the mold opens, the finished bottle is stripped off by retracting the blow pin through a stripper plate. The blowing pin contains channels for the circulation of blowing air and cooling water.

Many blow molded articles such as toy components do not have an integral aperture that can accept a blow pin. In such cases, blowing air can be supplied through a blow needle that punctures the parison wall after the mold closes (Figure 15.21). The needle can be advanced and retracted by means of an air or hydraulic cylinder and is lo-

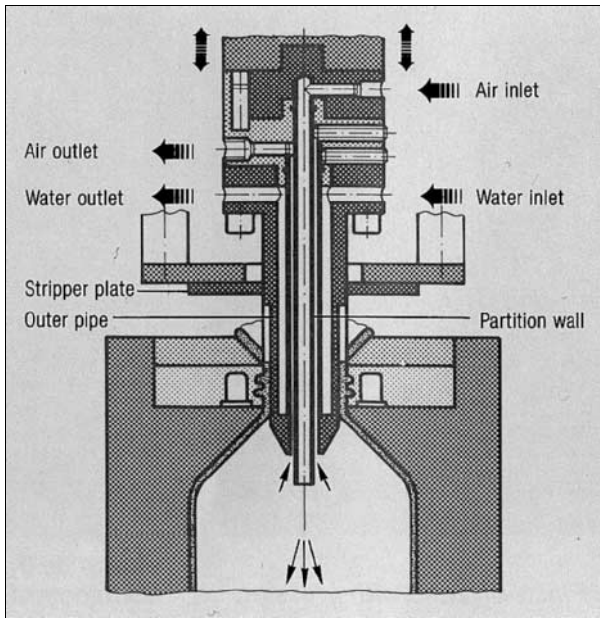


Figure 15.20 Example of calibrating blow pin.

cated at a point close to a pinch-off edge. The parison is gripped by the mold at this point and so is unable to deflect away from the advancing needle point. The blow needle leaves a small witness hole which is often acceptable within the function of the finished part. If not, it can be sealed by a secondary operation.

15.2.5 Venting and surface finish

When a parison is blown, a large volume of air must be displaced from the mold cavity in a short time. Because blowing is carried out at relatively low pressure, it is essential to provide venting to allow this air to escape without resistance. Unless a gloss finish is required on the molding, it is common practice to sandblast the cavity to a fine matte finish. This helps air to escape as the expanding parison touches the cavity face but it is not sufficient in itself. Vent slots may be cut at appropriate points into the mold parting face to a depth of 0.05 mm to 0.15 mm, and venting can also be provided within the mold cavity by means of inserts provided with vent slots, porous sintered plugs, or by holes with a diameter not greater than 0.2 mm. Such holes are machined only to a shallow depth and are relieved by a much larger bore machined from the back of the mold.

15.2.6 Cooling

Efficient mold cooling is essential for economical blow molding. Typically, up to 80% of a blow molding cycle is devoted to cooling. Molds are

constructed as far as possible from high thermal conductivity alloys, and water cooling channels are placed as close as possible to the surface of cavities and pinch-off zones. Because blow molding is a relatively low pressure process, the channels can be quite close to the surface and quite closely spaced before mold strength is compromised. The actual dimensions will depend on the material of construction but as a guide, channels may approach within 10 mm of the cavity and center spacing should not be less than twice the channel diameter. If the mold body is cast, the cooling channels can be fabricated in copper pipe to closely follow the cavity contours before being cast in place. If the mold is machined, channels

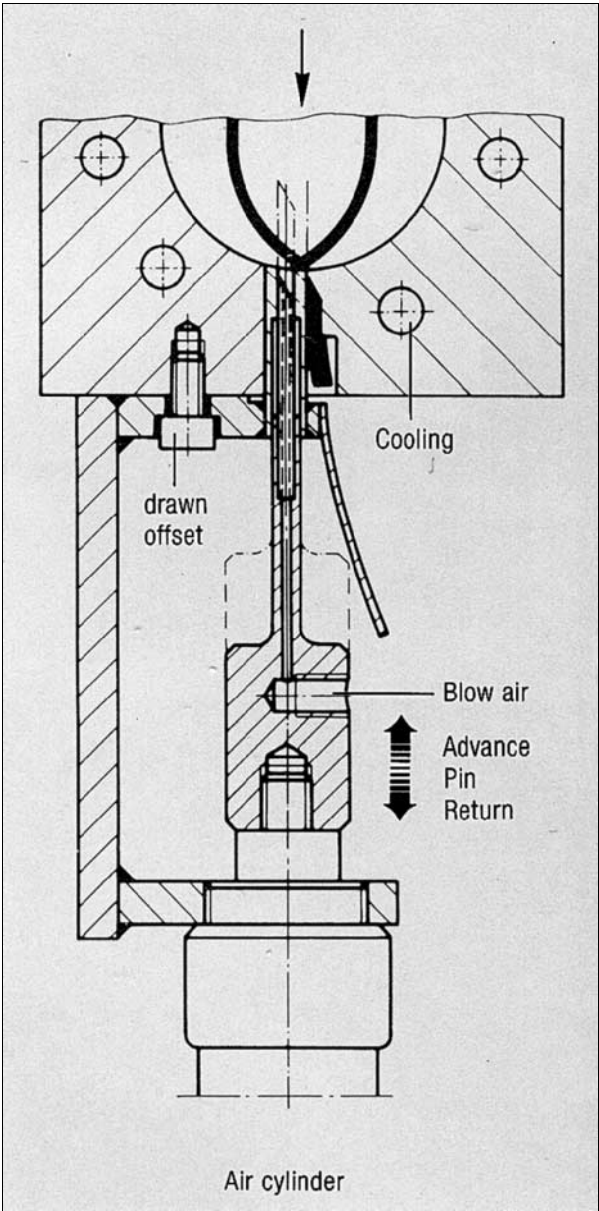


Figure 15.21 Example of blow needle.

will be produced by drilling and milling, and it is not usually possible to follow the cavity contours so closely. An alternative in cast molds is a large flood chamber. However, efficient water cooling requires turbulent flow and this may not be attained in a flood chamber or in large coolant channels. Many small channels are better than a few large ones. The cooling circuits will normally be zoned so that different areas of the mold can be independently controlled. The coolant flow rate should be sufficient to ensure turbulent flow and to

keep the temperature differential between inlet and outlet to about 3°C. Mold temperatures for polypropylene are typically 20°C to 40°C and the demolding temperature can be up to 60°C.

References for chapter 15:

1006, 1010, 1015, 1020, 1057, 1067, 1074, 1104, 1106, 1110, 1111, 1112, 1115, 1120, 1122, 1123, 1128, 1129, 1181, 1182, 1228, 1230, 1231, 1232, 1233

Introduction

Extrusion is the single most popular process for forming polypropylene, accounting for about 45% of consumption in the USA. Unlike injection molding, extrusion usually results in a semi-finished or intermediate article; one that needs further processing to arrive at an end product.

Fiber and filament accounts for some two-thirds of all polypropylene extrusion. The principal end products are carpet yarns, upholstery fabrics, heavy-duty webbing, industrial fabrics, geotextiles, disposable fabrics, woven sacks, twine, rope, cord, and strapping. The other major extrusion market is film. Polypropylene film is widely used in packaging, particularly for foodstuffs. Sheet and profile extrusion account for only a minor share of polypropylene consumption. The principal end products are sheet for thermoforming and office products, pipe, and tubing.

sential point is that extrusion always produces a prism-like object of constant cross-section.

The product cross-section is formed in a die; the extrusion process consists of raising a thermoplastic to its melt temperature and forcing it through this die. The heating and pressurizing device involves one or more screws operating in a heated barrel, and is known as an extruder. Downstream of the die, the extrudate is calibrated, cooled and packaged by an array of ancillary devices including vacuum calibrators, water tanks, cooling rolls, haul-offs, cutters, and winders. Upstream of the die, a melt pump may be interposed between the extruder and the die. The exact selection and arrangement of these component parts of an extrusion system will depend on the end product. These are discussed in detail later in this chapter. However, the principle of the extruder is common to all processes and will be discussed first.

16.1.1 The extruder

The function of the extruder is to heat the plastics material to a homogeneous melt and to pump it through the die at a constant rate. Because plastics extrusion is a continuous process, the melt preparation device must be capable of a constant output. Ram devices are essentially batch devices, and although it is possible to achieve a constant output by sequentially operating two or more rams, the method is of virtually no importance for the extrusion of thermoplastics such as polypropylene. Another possibility is the rotary extruder, a device in which rotating discs or rotors are used to generate shear. However, thermoplastics extrusion depends almost entirely on the rotating screw as a melt delivery device. Thermoplastics are characterized by low thermal conductivity, high specific heat, and high melt viscosity, so the preparation of a uniform melt and its delivery at adequate pressure and a constant rate poses considerable problems. These have been countered by the introduction of a variety of extruder types.

The principal variants are the single-screw and the twin-screw types. Of these, the single-screw extruder is by far the most versatile and popular. The twin-screw extruder may have parallel or conical screws, and these screws may rotate in the same direction (co-rotating) or in opposite directions (contra-rotating). Extruders with more than

16.1 Extrusion processes

Extrusion is a continuous process that involves forming a product in two dimensions. These X-Y dimensions determine the cross-sectional form of the extrudate, and this can be almost unlimited in scope, ranging from a simple tube to very complex forms used in window profiles. The third Z dimension is the length of the extrudate. In principle, it can be infinite. In fact, it is limited by practical considerations governing winding, reeling, storage or transport. The es-

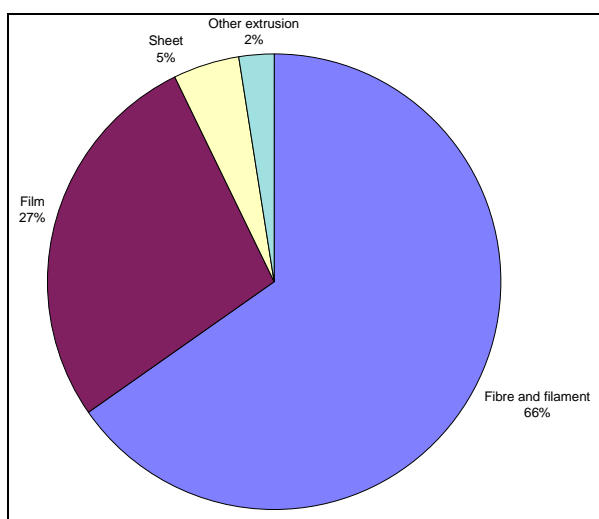


Figure 16.1 Polypropylene extrusion processes, USA, 1996. Source: Derived from [1216]

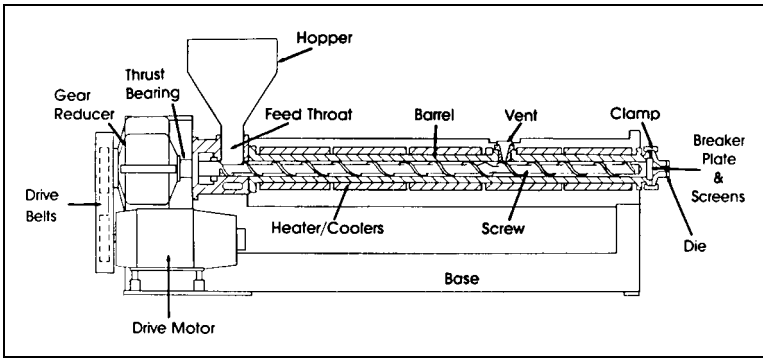


Figure 16.2 Typical single-screw extruder with a vented barrel.

two screws are known, for example the quad-screw extruder, but are not widely used. Twin-screw extruders are normally used when mixing and homogenization of the melt is very important, and in particular where additives are to be incorporated. Another application is for extruding PVC, particularly where the polymer is supplied in powder form. Polypropylene is normally extruded using a single screw machine (Figure 16.2).

The single-screw extruder consists essentially of a screw that rotates in an axially fixed position within the close-fitting bore of a barrel. The screw is motor driven through a gear reduction train, and is supported by a thrust bearing that opposes the force exerted on the plastics melt. A helical flight on the screw provides the drag-induced conveying motion that develops this force. The barrel is equipped with both heating and cooling means, and its downstream end is provided with an attachment device for a shaping die that determines the cross-section of the extruded product, known as an extrudate or extrusion. The upstream or inlet end of the barrel is equipped with a feed throat or aperture in the barrel wall where plastics material is input, generally in the form of granules or pellets. During its passage along the helical screw flight, this material is heated by a combination of conducted heat received from the barrel and mechanical shear heat derived from the mixing and kneading action of the screw. The output rate of the extruder is a function of screw speed, screw geometry, and melt viscosity. The pressure developed in the extruder system is largely a function of die resistance, and that depends on die geometry and melt viscosity. Extrusion pressures are lower than those encountered in injection molding, and are typically 1000 to 5000 psi (6.9 to 34.5 MPa). In extreme cases, extrusion pressures

may rise as high as 12000 psi (82.7 MPa).

The key determinant of extruder performance is the screw. The screw has three functions to perform; feeding and conveying the solid thermoplastics pellets, melting, compressing and homogenizing the material, and metering or pumping the melt to the die. The typical extruder screw (Figure 16.3) takes the form of a single constant-pitch flight that decreases in depth from the input end to the output end. The pitch is usually equal to the screw diameter. This is sometimes known as a square pitch screw; the resulting helix angle is 17.8°. The screw features three sequential zones, corresponding to the three functions of feeding, compression and metering.

Flight depth is usually constant in the feeding and metering zones, and decreases at a constant rate over the compression zone. The feed zone occupies about 50% of the screw length, the compression zone takes up 25 to 30%, and the metering zone accounts for the balance. The ratio of the flight depths in the feeding and metering zones is known as the compression ratio, and it affects the mixing and shear heating characteristic of the screw. The ratio of the screw length to its diameter is known as the L/D ratio; this has a bearing on mixing and uniformity of output. Polypropylene extrusion screws should have a high L/D ratio in the range 24:1 to 30:1, and a high compression ratio from 3:1 to 4:1.

The mixing performance of a single screw can be improved by the addition of mixing elements in the metering zone (Figure 16.4). These are sometimes teamed with or replaced by static elements such as pins in the barrel. Attention to the barrel can also improve the material conveying performance at the inlet, stepping up the output rate. A se-

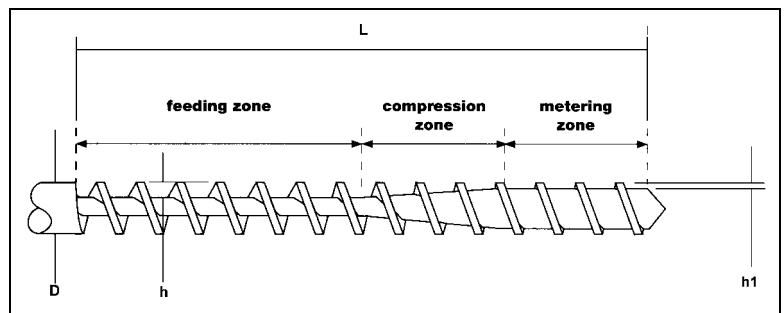


Figure 16.3 Features of a typical extrusion screw

Key: L = screw length, D = diameter, h = initial flight depth, h1 = final flight depth. L/D = length/diameter ratio, h/h1 = compression ratio

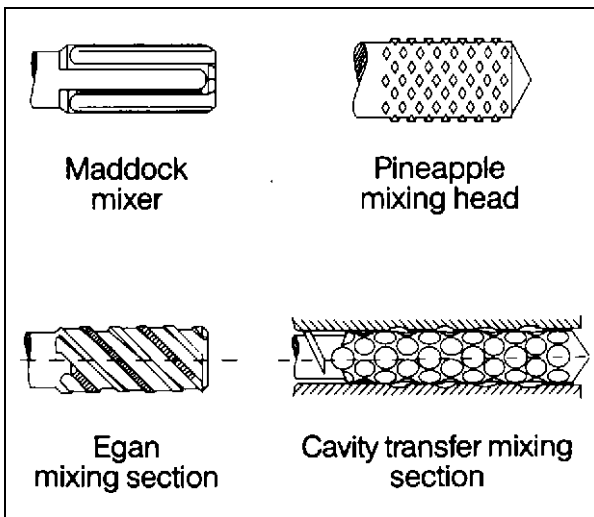


Figure 16.4 Mixing elements for polypropylene extrusion.

ries of axial grooves in the barrel wall (Figure 16.5), extending for at least three screw diameters is effective for polypropylene.

Variants on the single screw include the barrier or melt extraction screw (Figure 16.6) and the vented screw. Barrier screws have separate input and output flights that overlap in the mid-section of the screw where the plastics material is only partially melted. The barrier flights are slightly smaller in diameter than the main flights. Molten material passes through this clearance and proceeds to the metering zone while solids are retained for further heating. The barrier screw offers the potential for lower melt temperatures or higher output rates but is difficult to design and optimize. Vented screws, sometimes known as decompression screws or two-stage screws, are effectively two screws placed in series, with the second or downstream screw having a higher transport rate than the first. The upstream end of the screw is provided with conventional feeding compression

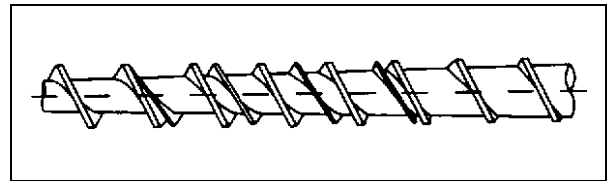


Figure 16.6 Section of barrier screw.

and metering zones but these are followed by a sudden increase in flight depth, and then by further compression and metering zones. The mid-screw increase in flight depth causes a sudden pressure drop in the plastics melt, and this allows any dissolved volatiles to boil out. The lack of compression at this point, coupled with the differential transport rates of the two screw sections, makes it possible to extract the volatiles through a port in the extruder barrel without the plastics melt emerging at the same time. Vented screws typically have an L/D ratio of greater than 30:1 and suffer from some instability in pumping output. Operating conditions are also constrained by the need to ensure that the vent does not plug with plastics melt. For these reasons, the use of vented screws is usually confined to materials likely to contain moisture, volatiles, or entrained air. Polypropylene is not prone to these problems so vented screws are not normally used in its processing.

16.1.2 Film extrusion

Polypropylene film can be produced either by extrusion casting or extrusion blowing processes. Each has its advantages and disadvantages. These basic processes result in film with a molecular orientation predominantly in the machine direction. Superior optical and physical properties can be developed by orienting the film in two orthogonal directions. The process is known as biaxial orientation and it can be applied to both tubular and sheet film. Regardless of process, film production lines include common downstream equipment such as haul-off, tensioning, and reeling stations. Other common features include static control units and corona discharge treaters to prepare the film surface for subsequent printing processes. A high purity melt, free of inclusions, is essential for film production. This is achieved by filtering the melt through a screen pack upstream of the die. The screen pack should be a fine mesh with a rating up to 3000 mesh/cm².

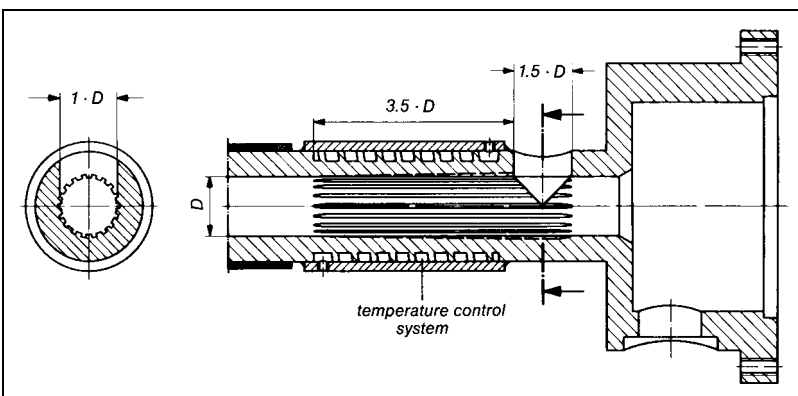


Figure 16.5 Grooved feed section of barrel.

16.1.2.1 Cast film

Cast film is produced by extruding the melt from a slit die and cooling it either by contact with a chill roll or by quenching in a water bath. Both processes are characterized by relatively high melt temperatures and rapid rates of film cooling. This results in films with low haze, good clarity and high gloss. Cast polypropylene films are used principally for food packaging and also for stationery use. Cast film grades typically have a melt flow index in the range 5.0 to 12.0 grams/ 10 min., and contain slip and anti-block agents to improve handling performance on packaging machinery.

Chill roll

In the chill roll cast film process, a plastics web is extruded from a slit die (Figure 16.7) against the surface of a water-cooled chill roll. The die is arranged to extrude vertically or obliquely downwards so that the film web is delivered approximately tangentially to the roll surface. The die is similar in principle to a sheet die but will usually not include a restrictor bar. Film thickness is partially regulated by the gap between the die lips but also by the rotational speed of the chill roll which is arranged so as to draw down and thin the melt web. Consequently, the die gap is set in excess of the desired film thickness. Typical die gap settings for polypropylene are 0.4 mm for films up to 0.25 mm thick, and 0.75 mm for film gauges in the range 0.25 mm to 0.6 mm. Most polypropylene films produced by chill roll casting are 0.02 mm to 0.20 mm thick. Die lip adjusters should allow the die gap to be varied at each adjustment point across the die width in order to allow control of the transverse film thickness. Film reel quality will suffer if the transverse thickness tolerance exceeds $\pm 5\%$ of target thickness. Relatively high melt temperatures in the range 240°C to 270°C are used to optimize the optical properties of the film. A constant temperature should be maintained across the die so that film draw-down rates and physical properties remain constant across the film web. Attempts to control film thickness by varying the temperature profile across the die will disturb these factors and reduce film quality. When the process is correctly regulated, the thickness uniformity of chill roll cast film is substantially superior to blown film.

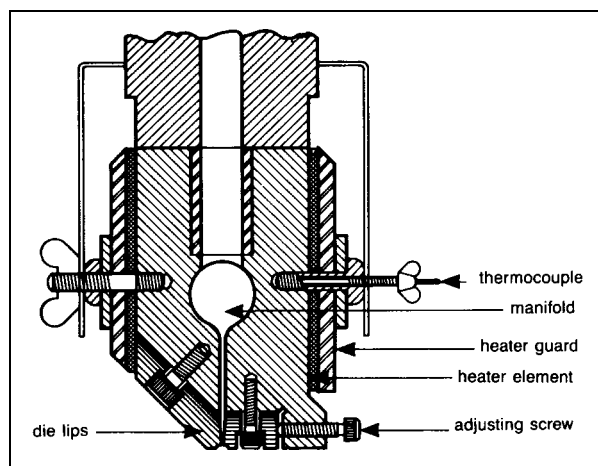


Figure 16.7 Typical slit die for cast film.

The die is maintained in close proximity (typically 40 mm to 80 mm) to the chill roll so that the low-strength melt web remains unsupported for a minimal distance and time (Figure 16.8). If the die is too close, there is insufficient space for thickness draw-down and widthwise neck-in to take place in a stable manner. The web flows on to the water-cooled chill roll with a wrap-around of 240° or more before passing to a second chill roll, and then proceeding to edge trimming, tensioning, and wind-up stations. The first chill roll is critical to process quality. The cooling capacity must be sufficient to chill the film at high output rates, and the temperature gradient across the width of the roll should not exceed $\pm 1^\circ\text{C}$. The actual roll temperature depends on film gauge, line speed and roll diameter; a temperature of about 20°C is common. The chill roll drive speeds must be very precisely regulated to control film draw-down and finished

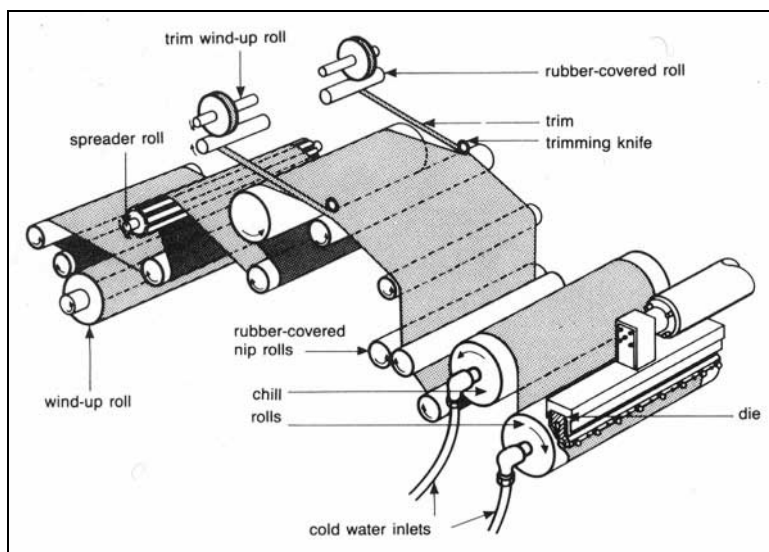


Figure 16.8 Typical chill roll cast film line.

thickness. The chill rolls normally have a mirror finish but a matt finish roll is often used for producing stationery films.

At line speeds greater than 30 metres per minute, there is a tendency for a thin cushion of air to become trapped between the film and the chill roll. This results in slow and uneven cooling, affecting the appearance and properties of the film. Two measures are adopted to counteract the problem (Figure 16.9). An air knife delivers a streamline jet of filtered air that impinges on the film just beyond the point of first contact with the chill roll and presses it against the roll. The air is supplied through a narrow slit of about 1.5 mm gap, and controlled at a low differential above atmospheric pressure. An optimum air knife setting improves film clarity and gloss but excessive pressure induces melt vibration and mars the film surface. The second measure is the provision of a vacuum box, associated with the die, and operating close to the chill roll surface just ahead of the extruded melt web. The vacuum box removes any condensates that have been deposited on the roll by the film, and tends to draw air out of the interface between film and roll.

The film temperature should be close to ambient at the film wind-up station otherwise the reel will continue to shrink after cooling, causing stretch marks and corrugations, and accentuating any variations in thickness. Winding tension should be sufficient to ensure the integrity of the reel but otherwise should be kept low to allow for a small amount of post-winding shrinkage that will tighten the reel.

As in other plastics processes, the cast film process depends on many interactive variables, so that any defect may have one of several causes. A remedy for one defect may introduce another, so proc-

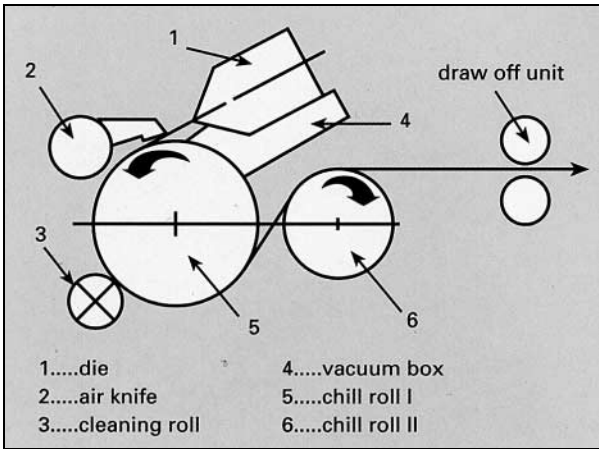


Figure 16.9 Detail of chill roll process.

ess problem solving is not straightforward. With these provisos, the trouble shooting chart (Table 16.1) provides a useful guide for problem solving.

Water quench

The water quench cast film process (Figure 16.10) is similar in concept to the chill roll process and uses similar downstream equipment. A water bath takes the place of the chill roll for film cooling, and by cooling both sides of the film equally, it produces a film with slightly different properties compared to chill roll cast film. The extruder slit die is arranged vertically and extrudes a melt web directly into the water bath at close range. The bath is typically maintained at 20°C. The film passes under a pair of idler rollers in the bath and, for any given rate of extrusion, it is the rate of downstream haul-off that regulates film draw-down and finished thickness.

The speed of the process is limited by the tendency of the film to carry over water from the quench bath. The presence in the film of slip and

Table 16.1 Chill roll film trouble shooting chart.

Problem	Possible cause	Suggested remedy
Poor clarity	Cooling rate too low	Increase melt temperature Reposition air knife Increase air knife pressure Reduce chill roll temperature
Variable optical properties	Temperature gradient across the chill roll	Adjust chill roll coolant supply Check chill roll cooling circuits
Plateout	Poor chill roll contact	Increase chill roll wrap-around Adjust air knife
Flow defects	Melt temperature too low	Increase die and adapter temperatures
Brittle or fibrous heat seals	Melt temperature too high	Decrease die and adapter temperatures

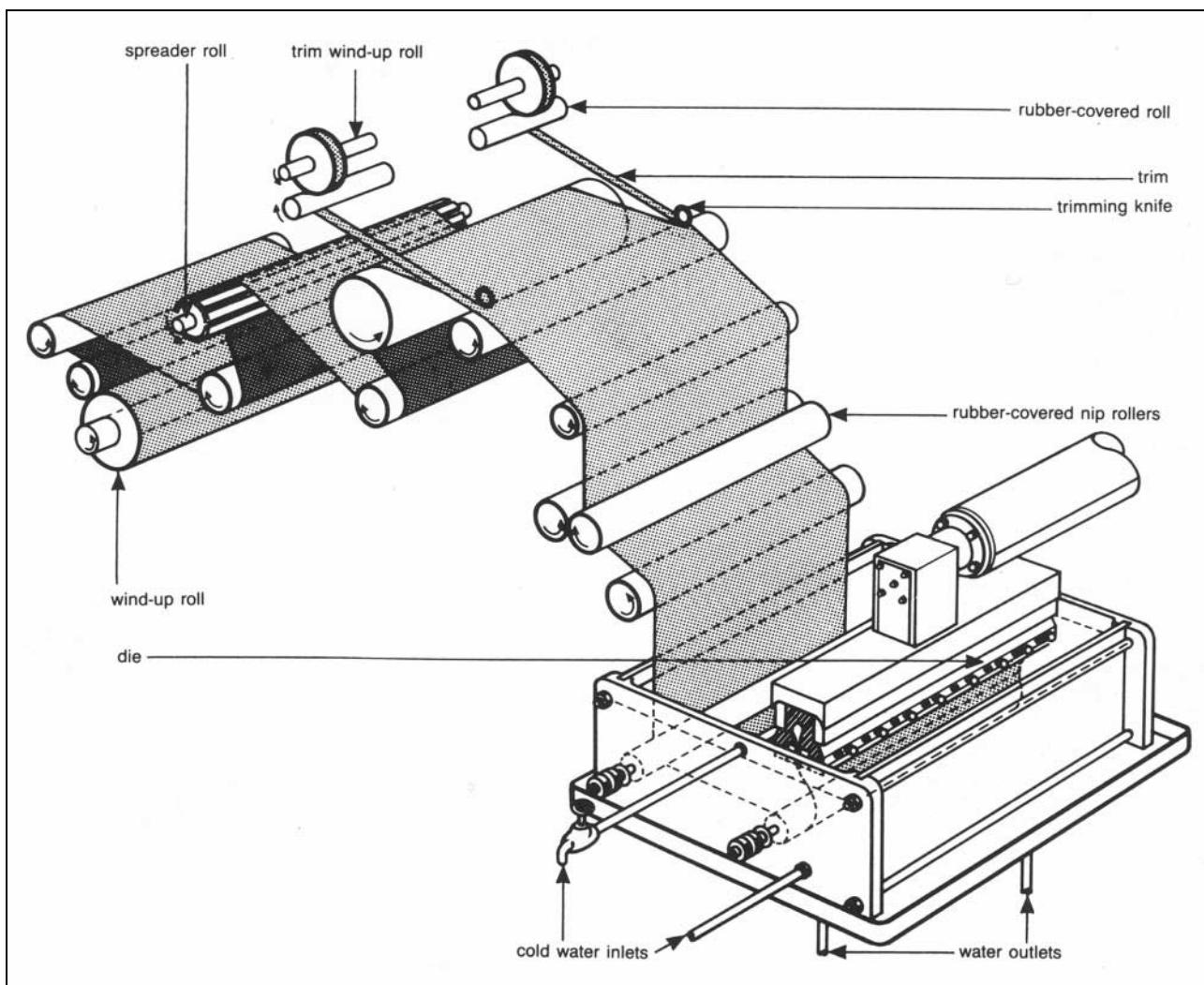


Figure 16.10 Typical water quench film line.

anti-static additives increases this tendency. Surface defects can also arise from rippling in the water bath. The very rapid quenching induced by the water bath reduces crystallinity and produces a tough film, so the process is often preferred to make films for strapping and packaging tapes, generally in the thickness range 0.07 mm to 0.25 mm.

16.1.2.2 Blown film

The blown film process involves extruding a relatively thick tube which is then expanded or blown by internal air pressure to produce a relatively thin film. The tube can be collapsed to form double-layer layflat film or can be slit to make one or two single-layer film webs. The air cooled blown film process is in very widespread use for polyethylene films but it presents greater difficulty when used with polypropylene. The water quench process is the generally preferred method of producing blown polypropylene film.

Water quench

The water quench blown film process is also known as the tubular water quench process, and uses a tube die that is arranged to extrude vertically downwards (Figure 16.11). The process needs a melt strength greater than that required by cast film processes so lower melt temperatures are used, typically in the range 190°C to 230°C. The die should be designed for constant output rates and thickness at every point around the annular die gap. This requires streamlined internal melt flow paths and precise multi-point means of centering the mandrel within the die ring. The die gap is typically about 0.4 mm, with a short land length and a die entry angle of about 10°. Close thickness tolerances are difficult to achieve with the blown film process; variations around the bubble can be limited to perhaps $\pm 10\%$ of the target film thickness. To distribute these variations evenly, blown film lines may include ro-

tating or oscillating motions applied either to the die, the extruder, or the haul-off.

As it emerges from the die, the tube passes through an air ring that lays a large volume of low velocity cooling air over the external surface. At the same time, the tube is pressurized internally by air supplied through the die mandrel. The air is confined by downstream nip rollers, so it inflates the still soft tube to form an enlarged bubble. This distends and thins the tube walls to the final film thickness. The bubble size is limited and calibrated by an annular water cooling weir that covers the outer bubble surface with a stream of cooling water. The water contact is directed and controlled by an annular flexible skirt. The water temperature should be 5°C to 10°C for polypropylene homopolymer, or 10°C to 30°C for random copolymer. The rapid bubble cooling induced by the water stream limits crystallinity and produces a clearer film than is possible by the air cooled blown process.

After cooling, the film passes through a collapsing frame and proceeds through de-watering, haul-off and winding stations. Slit film reeled as two separate webs is preferred to layflat film because blocking between the layflat layers is pronounced with polypropylene films.

The water quench blown film process is normally used with smaller extruders with screws up to 65mm, and is preferred mainly for bag making films because of the better balance of orientation between the machine direction and the transverse direction.

Air cooled

The air cooled blown film process uses a similar die to the water quench process but it is normally arranged to extrude vertically upwards. The film passes through a similar but higher capacity air cooling ring and is inflated in the same way. The principal difference is that the bubble is much longer in the air cooled process than it is in the water quench process. This extra length is necessary for bubble cooling to be completed by air contact. Line speed is effectively limited by the bubble length available for cooling. Downstream equipment includes bubble calibration, a collapsing

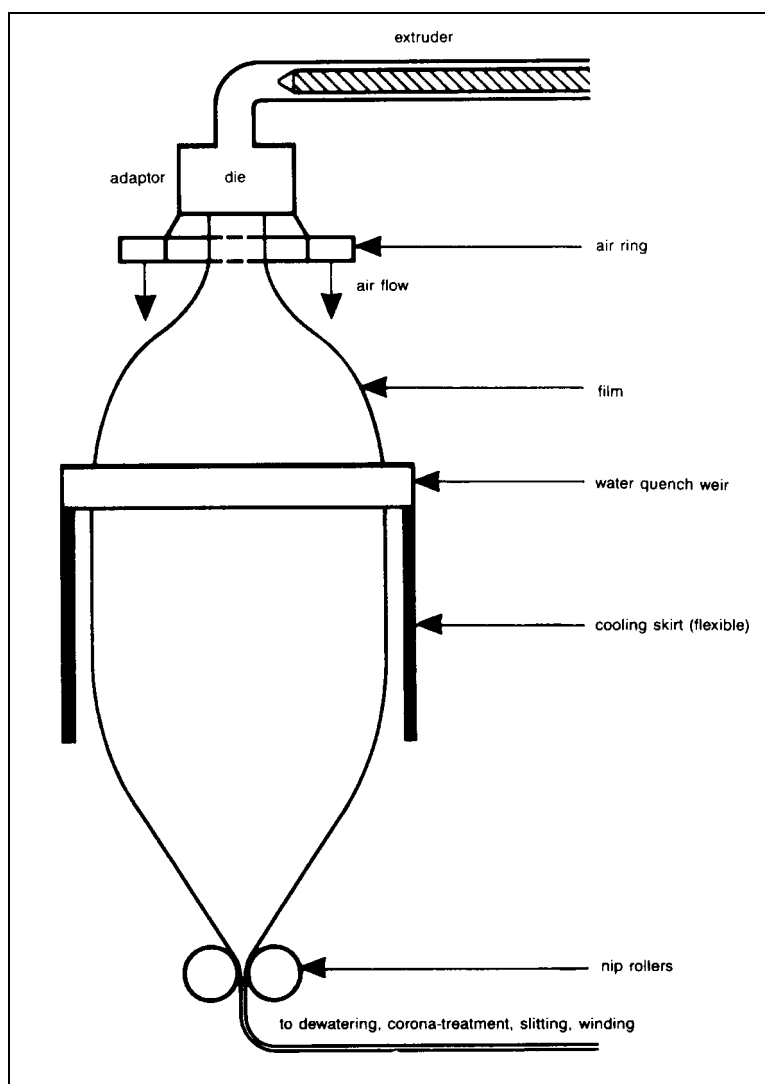


Figure 16.11 Water quench process for blown film.

frame, and haul-off, tensioning, and reeling stations. Film thickness and process control is a balance between cooling rate, bubble length, blow-up ratio, and film tension. Stability is much harder to achieve with polypropylene than with polyethylene, so the process is of limited significance to polypropylene converters.

16.1.2.3 Biaxially oriented film

Biaxially oriented polypropylene film (BOPP) is a highly transparent stiff film produced in thin gauges ranging typically from .012 mm to .040 mm. It is widely used for the packaging of foods, cigarettes and other items, where it has largely supplanted cellophane. The film is produced by stretching an extruded sheet or tube in two orthogonal directions — the machine direction and the transverse direction. Stretching is carried out at a temperature below the melting point of the

polymer and results in a partial orientation of polymer molecules in the direction of stretch. In principle, biaxially oriented film is isotropic — its properties are the same in both the machine and transverse directions. In practice, film produced by the tenter process tends to be more highly oriented in the machine direction whereas the blown process produces a film that is more nearly isotropic. Capital costs for a blown BOPP film line are substantially less than those of a tenter line. Biaxially oriented polypropylene film is typically produced from grades with a melt flow index in the range 2.5 to 4.5 grams/ 10 min.

Blown

The blown process, also known as the tubular or bubble process, uses a tubular die to extrude a relatively thick-walled tube in a vertical direction, either upwards or downwards. Downwards extru-

sion (Figure 16.12) allows the tube to be quenched rapidly in a water bath after which it is collapsed as a layflat for passage over nip and idler rollers. The film passes through a reheating tunnel where it is raised to a temperature above the softening point but below the melting point. The heated tube is then inflated by internal air pressure that forms a bubble in which the film is stretched in all directions. Some machine-direction stretch may take place in the ovens upstream of the bubble; the haul-off rate can be adjusted if necessary to secure an orientation balance. Bubble cooling is provided by an air ring similar to that used in other blown film processes. Subsequent calibration and bubble collapsing operations are also similar.

At this point, the film retains shape memory. If it is reheated, it will shrink and revert to dimensions approaching its pre-stretch shape. If a shrink film is required, the layflat is edge-trimmed, separated and reeled as two webs at this stage. Most biaxially oriented polypropylene film is of the non-shrink variety and this is produced by subjecting the layflat to a further heat treatment in which it is annealed or heat set under tension in an oven. The annealing temperature is set slightly higher than the stretching temperature.

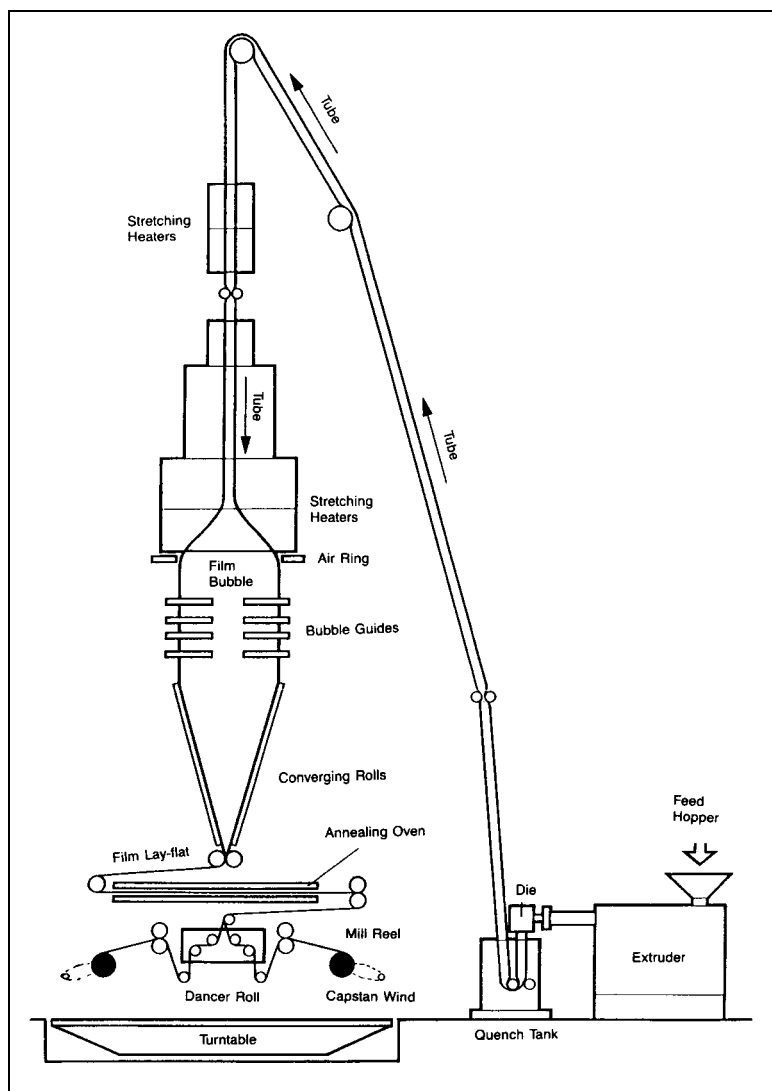


Figure 16.12 Blown process for biaxially oriented film.

Tentered

Tentered biaxially oriented film is produced by mechanically stretching the film in a tenter machine. This takes its name from the tenter frame originally used for stretching cloth between grips known as tenterhooks. The process is occasionally, and apparently without etymological justification, called stentering.

Simultaneous tentering is possible, involving complex movements of the film edge grips so that the film is stretched in the machine and transverse directions at the same time. However, the process is mechanically complicated and it is difficult to adjust the balance between the stretch directions, so the two-step tenter process (Figure 16.13) is the one usually adopted for polypropylene film.

The process starts with the production of a relatively thick chill roll cast film. This is then stretched in the machine direction by passing it around

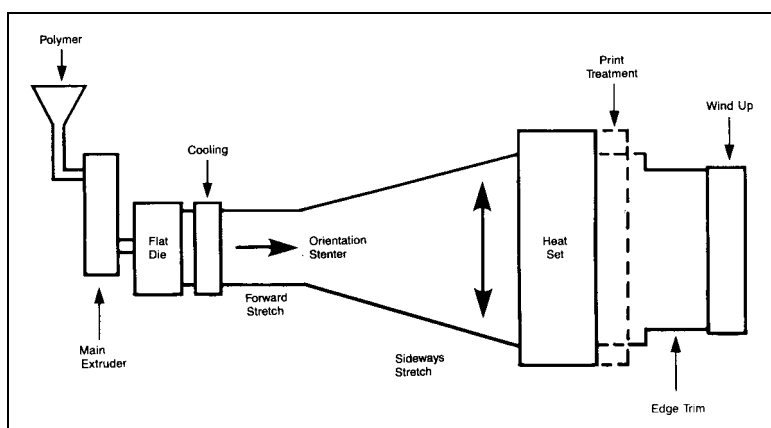


Figure 16.13 Tenter process for biaxially oriented film.

heated rollers rotating at controlled and increasing speeds in excess of the extrusion speed. The degree of stretch is controlled by varying the roll speeds. Typically, stretch in the machine direction is about 4.5:1.

When machine direction stretching is complete, transverse stretching is applied by the tenter machine. This consists essentially of a temperature regulated tunnel in which the film edges are gripped by chain-driven tension clips running on divergent paths. As the film passes through the tunnel it is progressively stretched in the transverse direction as the clips diverge. The edge grip mechanism must withstand high cross loads of up to 3.5 kN per clip, and be capable of operating at line speeds of up to 450 metres per minute. Transverse stretch is controlled by varying the divergence of the edge clip paths. A ratio of 8:1 is typical.

Biaxially oriented polypropylene film is not readily heat sealable. This is a prime requirement for packaging films so BOPP is normally given a surface coating of a heat sealable polymer, such as a coextruded polypropylene random copolymer. The concept of coextrusion can be applied to most extrusion processes.

16.1.3 Extrusion coating

Extrusion coating is the process of applying a thin bonded film of a plastics material to a continuous non-plastics substrate such as paper, board or foil. The process is similar to chill roll film extrusion. A high melt temperature is employed with a downwardly directed slit die to produce a low viscosity melt web that adheres to the substrate. If necessary, the substrate may be given a pre-treatment to improve adhesion. The web is directed against the surface of the substrate immediately before its entry

into the nip between a pressure roll and a chill roll. The coating thickness is determined by the extrusion rate and the line speed of the substrate. The chill roll controls the surface finish of the coating. Extrusion coatings are typically applied in thin layers, ranging down to 0.005 mm.

16.1.4 Sheet extrusion

Sheet is usually defined as thicker than 0.25 mm (0.01 in); anything thinner is classed as film. Polypropylene sheet is extruded up to 30 mm thick and in widths up to 2500 mm. The sheet material can be thermoformed, or fabricated by blanking, punching, machining, and welding. A hinge or crease can be formed in polypropylene sheet by a cold coining technique. The key characteristics of polypropylene sheet are a good ratio of strength and rigidity to thickness, toughness, moisture resistance, resistance to sterilization procedures, good moisture barrier properties, chemical resistance, and non-toxicity. The thinner gauges are used principally for thermoformed food packaging. Other applications include stationery and office products, thermoformed tote trays for pharmaceutical use, fabricated tanks, ducting, and wall cladding for the food industry. Sheet grades of polypropylene have a low melt flow index (MFI), typically in the range 2.0 to 6.0 grams/10 min. for thin-gauge grades. Grades for products of intermediate thickness have an MFI of 1.8 to 2.2 grams/10 min., while thicker sheets are usually produced from grades having an MFI of 0.8 to 1.5 grams/10 min.

16.1.4.1 Production

Extruded sheet is produced with a die having a wide slit-like outlet (Figure 16.14). The internal flow geometry is designed to transform the cylindrical melt flow received from the extruder to this slit form, while at the same time ensuring that the melt flow velocity at the slit exit is constant at all points across the slit width. This is difficult to achieve, particularly in wide sheet dies, and a number of solutions have been devised to deal with the problem. The usual approach is known as the 'coathanger' die, so called because the internal flow passage tapers from the die center to the edges. By offering a greater resistance to flow in the die center, this tends to equalize flow rates across the die. Most sheet dies include two other regulating devices. An internal adjustable dam known as a restrictor bar or choker

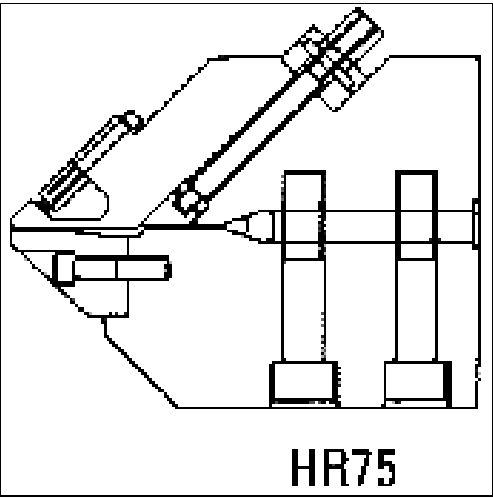


Figure 16.14 Typical sheet extrusion die.

bar is positioned in the flow path to the die exit and acts as a coarse regulator. Fine regulation is achieved by adjustment of the die lips at the die exit. The upper die lip includes a thin section that can be flexed elastically by the action of manual or automatic adjuster bolts, so that the die exit gap can be varied across the die width. The die gap should be set in the range 0% to 10% greater than the desired sheet thickness.

From the die, the sheet passes immediately to a cooling and finishing device in the form of a roll cooling stack (Figure 16.15). The usual configuration is a three-roll vertical stack with the sheet entering at the nip between the upper two rolls. Variants include up-stack working where the sheet enters between the lower two rolls, a horizontal roll stack used with a vertical die for low viscosity melts, and a two-roll stack for thinner sheet gauges. The function of the stack is to cool and polish the sheet. Alternatively, an embossed roll may be used to impart a texture to the sheet surface. Close temperature control of the rolls is critical; the temperature variation across the roll should be no more than 1.5°C. Roll temperatures depend on sheet thickness and production rate, and on whether a gloss surface is required. If so, the appropriate sheet surface must be maintained at least 110°C until it contacts the polishing roll. For

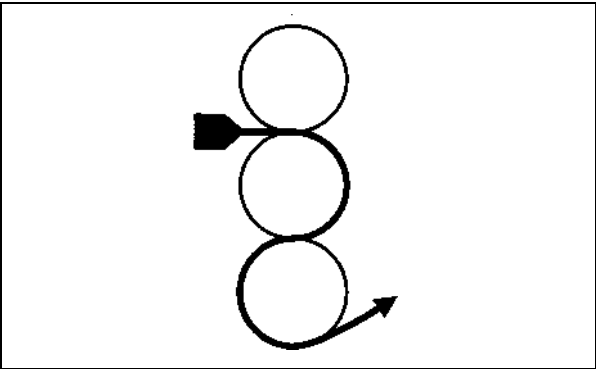


Figure 16.15 Three-roll sheet cooling stack.

polypropylene, the temperature of the polishing roll is typically 100°C to 120°C.

Polypropylene requires a high roll closing force in the nip region, particularly for thinner gauges of sheet. The roll stack should be capable of exerting at least 55 kg per centimeter of nip width. Any excess of material resulting from an oversize die gap will appear at the entry nip as a rolling melt bank. A small bank compensates for output variations from the extruder; too large a bank leads to poor thickness distribution. The sheet extrusion line is completed by a continuous edge trimmer, a pair of traction rolls for maintaining sheet tension, and a reeling device for thin

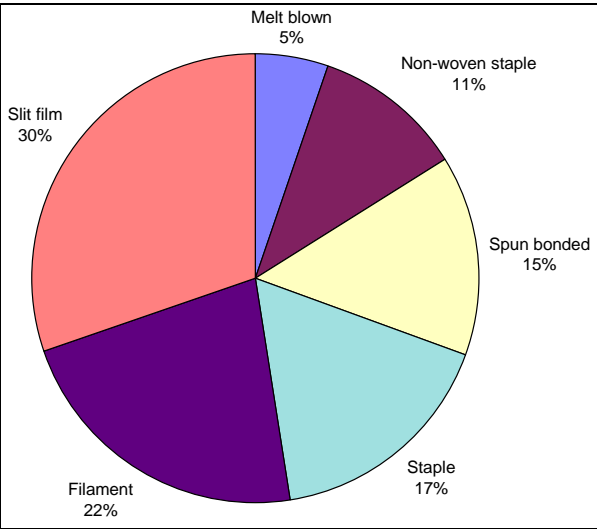


Figure 16.16 North American fibers market 1995; market share by process.

Table 16.2 Influence of die and roll stack variables on sheet characteristics.

Variable	Orientation	Transparency	Gloss	Stiffness	Impact resistance
Die gap	>	–	–	–	–
Melt temperature	<	–	>	–	–
Roll temperatures	–	<	>	>	<
Roll speeds	>	<	>	>	<

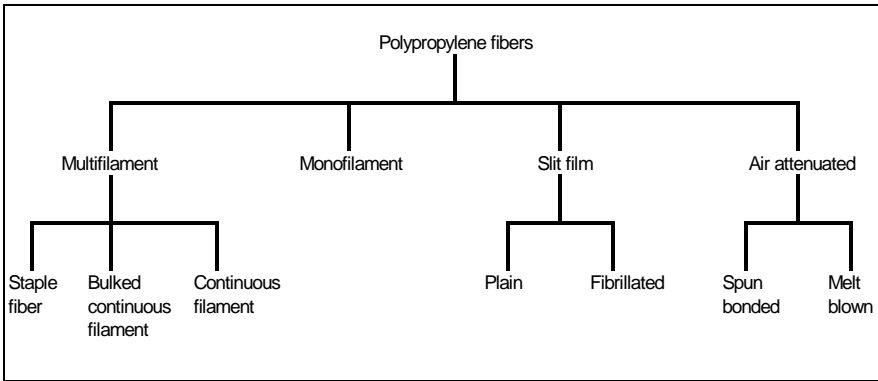


Figure 16.17 Relationship between polypropylene fiber processes

sheet or a cutter and stacker for thick sheet. The table (Table 16.2) summarizes the effect of die and roll variables on sheet characteristics.

16.1.5 Fiber extrusion

Two-thirds of all extruded polypropylene goes into the manufacture of fibers and filaments (Figure 16.16). A wide array of manufacturing processes are used to produce many different fiber types aimed at specific end use applications (Figure 16.17). Of course, processes and applications overlap to an extent but it is nevertheless possible to draw broad distinctions to classify the various options (Figure 16.18). The biggest single category of polypropylene fiber is slit film with a 30% share of the total. In its non-fibrillated form this is arguably not a fiber at all, but it is classified as such because it is used entirely in textile applications. Filament fibers — multifilament and monofilament — account for some 22% of polypropylene fiber production. Air attenuated fibers constitute about 20% of production.

16.1.5.1 Multifilament

Multifilament yarns are composed of bundled individual filaments of 75 denier or less. The denier

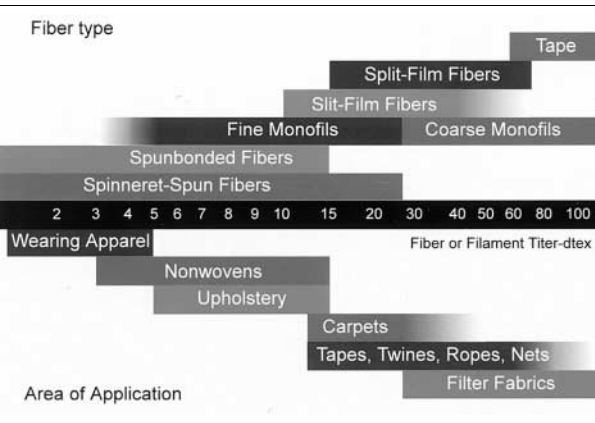


Figure 16.18 Fiber types and applications.

number represents the weight in grams of 9000 metres of yarn, and is a measure of linear density. An alternative unit is the tex, representing the weight in grams of 1000 metres. Yarn linear density is sometimes expressed in decitex (1 dtex = 0.1 tex).

All multifilament fiber extrusion processes involve the basic steps of spinning, quenching and stretching, but the subsequent treatments vary. Staple fi-

bers are produced by chopping the multifilaments into short lengths. Bulked continuous filament (BCF) and continuous filament yarns are not chopped, but the BCF is given a treatment to impart a three-dimensional bulk. Multifilament fiber is usually produced from polypropylene homopolymer with a high melt flow index from 12.0 to 38.0 grams/ 10 min.

Continuous filament

The multifilament extrusion process uses an extruder to prepare a polymer melt stream for extrusion through a special type of die known as a spinneret. This involves passing the melt through a very large number of very small holes, and this gives the process a number of distinctive features. The process demands a low melt viscosity so, as we have already noted, high melt flow index grades are used, and at relatively high melt temperatures in the range 230°C to 260°C. Because the holes in the spinneret are very small, an exceptionally high degree of melt filtration is necessary to screen out foreign particles that would otherwise clog the spinneret or cause the filament to fracture in the stretching operation. Unlike other forms of extrusion where the die is mounted on an adapter at the extruder outlet, the fiber-forming spinneret is mounted at some distance from the extruder and is connected to it by a heated melt manifold system. This arrangement makes it possible to build down-working (Figure 16.19) or up-working melt spinning systems. Pressure losses in the melt distribution system are the reason for another distinctive feature — the use of melt pumps to develop the necessary pressure flow rate for spinning.

From the extruder, the melt stream passes to a filter system operating typically at the 40 micron level. The filtered stream then proceeds to the spin-

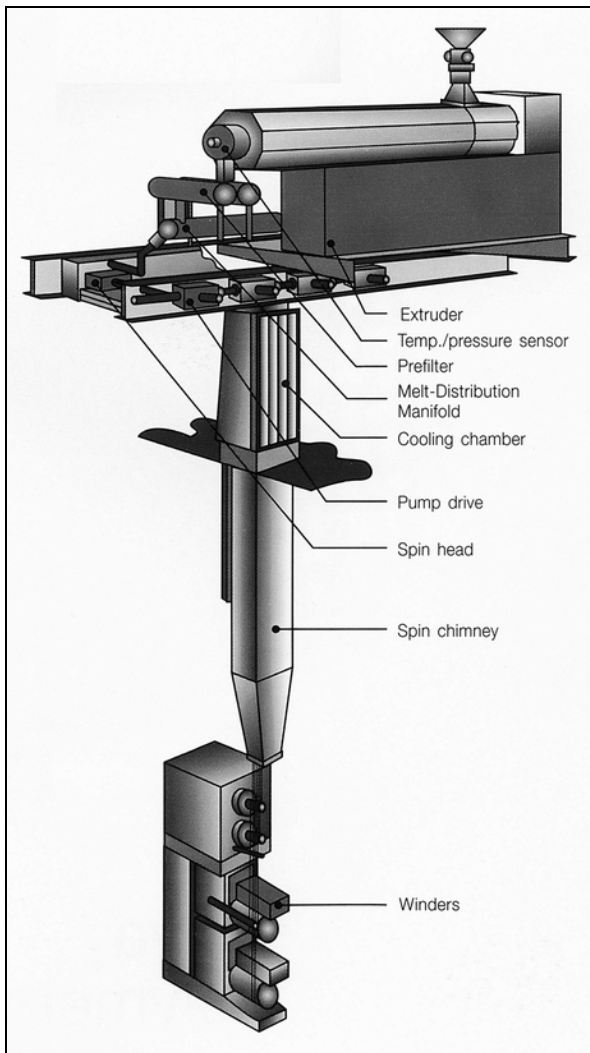


Figure 16.19 Typical multifilament melt spinning system.

ning beam, consisting of a heated melt distribution manifold feeding a number of spinning packs via melt metering gear pumps. Each spinning pack is effectively a separate extrusion head, consisting of a final filter ahead of a streamline flow chamber housing the spinneret. The spinneret is a rectangular plate die, typically provided with 200 or more holes arranged in a grid formation. The spinneret holes may be simple cylindrical bores but may also be profiled to create fibers with improved wicking properties. Common profiles include trilobal, quadrilobal, delta and dogbone shapes. The land length of the spinneret holes is typically in the range 5 to 15 times the hole diameter.

As the melt emerges from the spinneret hole, it passes down a spin chimney where it is cooled or quenched in a streamline air flow operating at a controlled temperature. Towards the exit of the spin chimney, the multiple fibers converge into a

multifilament bundle or yarn and are hauled off by godet rolls.

The final step is yarn stretching or drawing to orient the molecular chains to a high degree in the machine direction. Orientation also reduces the diameter of the fibers. The process is performed at a temperature close to but less than the melt temperature, by stretching between rolls operating at a speed differential. The orientation process has a critical influence on the properties of the finished fiber. The orientation is set by an annealing step and the continuous filament yarn is wound on spools or bobbins for subsequent use in textile operations.

Continuous filament yarns are used for woven industrial fabric and filters.

Bulked continuous filament

Bulked continuous filament yarn is produced in exactly the same manner as continuous filament but is given an additional treatment before final spooling. The purpose of this treatment is to improve the handling, feel and elasticity of a textile article manufactured from the yarn. There are a number of different bulking treatments, the aim always being to produce minor distortions to the filaments. The principle is to heat the yarn close to the melting point by means that perturb the filaments, using steam jets, turbulent hot air, or a hot knife edge. The bulking process is completed by cooling the yarn, slightly stretching it and then relaxing it to produce a slightly contracted bulked appearance.

Bulked continuous filament yarns are typically produced from 3 to 30 denier, and are used extensively in knitted and woven fabrics for clothing, upholstery and other applications. The fibers are also used in the production of tufted carpets.

Staple fiber

Staple fiber consists of intermingled short length multifilament fibers, and as a textile concept is similar to natural fibers such as wool or cotton. Staple fiber is produced in much the same manner as continuous filament but the filaments are finer and are collected together in large numbers in a loose rope or tow. The spinneret contains a very large number of holes, 10,000 or more and sometimes ranging as high as 50,000. The tow is passed through a crimper that imparts a small zigzag configuration to the filaments and is then chopped into short lengths from 5 mm to 60 mm. The chopped fibers are baled in random orientation for use in any textile process conducted with staple fiber.

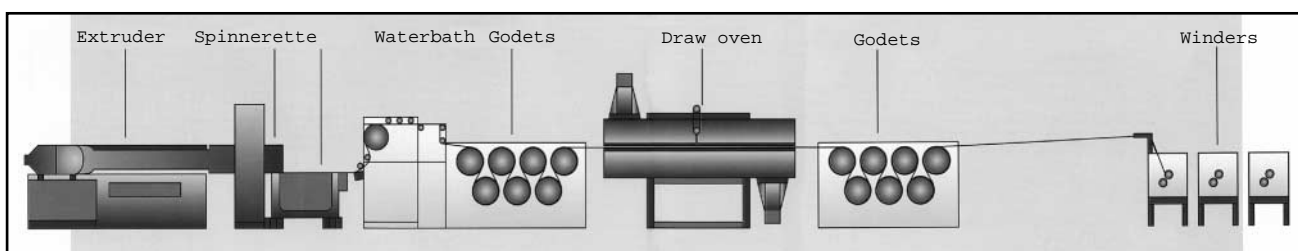


Figure 16.20 Typical monofilament yarn line.

The denier range is typically 1 to 10. Uses include clothing and other fine fabrics.

16.1.5.2 Monofilament

As the name implies, monofilament yarns consist of a single filament. The filament size is much larger than those found in multifilament yarn. Consequently, monofilament is relatively stiff and is used mainly for the production of rope and twine. The fiber size range is typically 75 to 5000 denier. Monofilament fiber is usually produced from polypropylene homopolymer with a relatively low melt flow index in the range 3.5 to 5.0 grams/ 10 min.

The monofilament process (Figure 16.20) includes aspects of both the melt spinning and slit film processes. The extruder is equipped with a melt pump immediately upstream of a spinneret that extrudes relatively thick filaments ranging from 0.08 mm to 3.0 mm in diameter. The filaments are quenched in a water bath and are hauled off by godet rolls. Orientation is performed by reheating and stretching in an oven under tension applied by a second haul-off. An alternative orientation process uses heated godet rolls in place of the oven.

16.1.5.3 Slit film

Slit film fiber is produced by slitting a cast film into narrow tapes that are then uniaxially oriented in the machine direction. The film may be cast by the chill roll or water quench processes described elsewhere in this chapter. The slit film fiber (plain tape) may be used as it is in weaving processes, or it may be given a subsequent fibrillation treatment to impart a fibrous character.

Plain tape

The cooled cast film web is slit into narrow multiple parallel tapes at a tension point immediately upstream of the first set of godet rolls that anchor the tapes ahead of the orientation oven. A second set of godet rolls applies a stretching tension to the tapes which are heated to a temperature just below the melting point. Draw ratios typically range from 1:5 to 1:8. Heated rolls may be used as an alternative to the draw oven. Finally, the tapes are annealed to set the orientation, and are wound on spools for subsequent use in textile operations.

Slit film fiber is used in woven form mainly for heavy-duty applications including carpet backing, coating substrates, geotextiles, and industrial sacks and bags.

Fibrillated tape

Fibrillated tape fiber is produced in the same manner as slit film fiber (0), except that a great draw ratio of up to 1:10 is used and a fibrillation step is added to the process. The slit film tapes are fibrillated by passing them over a rapidly rotating roll fitted with staggered rows of pins. As the pins are traveling faster than the tapes, they make a series of short discrete cuts in the longitudinal direction of the tapes.

Fibrillated tape fiber is used for producing packaging and baling twines, and in the manufacture of artificial grass.

16.1.5.4 Air attenuated

Air attenuated fiber processes use an air stream to draw and orient very fine fibers that are then deposited as a randomly oriented mat to form a non-

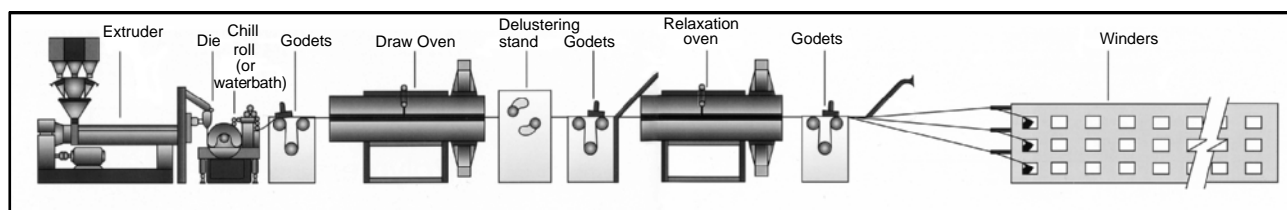


Figure 16.21 Typical slit film tape line.

woven fabric. Uses include diapers and sanitary items, disposable clothing, industrial and domestic wipes, table cloths, battery separators, carpet backing, and geotextiles. The two principle variants of the air attenuation method are the spun bonded and melt blown processes. These processes require polypropylene grades with a high melt flow index of 24.0 to 38.0 and a narrow molecular weight distribution.

Spun bonded

In the spun bonded fiber process, an extruder and spinneret are used to produce filaments in the same manner as the continuous multifilament process. The filaments are initially quenched in air and then pass to an air venturi aspirator where they are exposed to a high-velocity stream of heated air that stretches and orients the filaments. Draw-down takes place at very high speeds up to 5000 metres per minute. At the outlet of the aspirator, the fibers are randomly blown on to an endless mesh belt where, with suction assistance, they form a mat or web. The web is subsequently stabilized by a variety of means including hot air bonding, adhesive bonding, stitching or needle

punching. The web may be calendered to provide a smooth or textured surface, and may also be oriented by tentering. The constituent fibers of a spun bonded web may be as fine as 3 dtex.

Melt blown

The melt blown process produces a non-woven web in a single operation by omitting the initial air quench step. As they leave the spinneret, the melt streams are entrained by high-speed obliquely aimed hot air jets that produce very fine filaments of as little as 0.1 dtex. Web formation and stabilization is performed by the same means used for spun bonded webs. The process is sometimes combined with a spun bonded line to produce a non-woven fabric with different characteristics on either face.

16.1.6 Pipe and tube extrusion

Polypropylene pipes and tubes are extruded in a wide range of sizes, from drinking straws up to pipes of 1600 mm diameter and more. The principal characteristics are very good resistance to heat ageing, high heat distortion temperature, low friction losses, light weight, and high resistance to attack by chemicals and soils. Heat stabilized grades

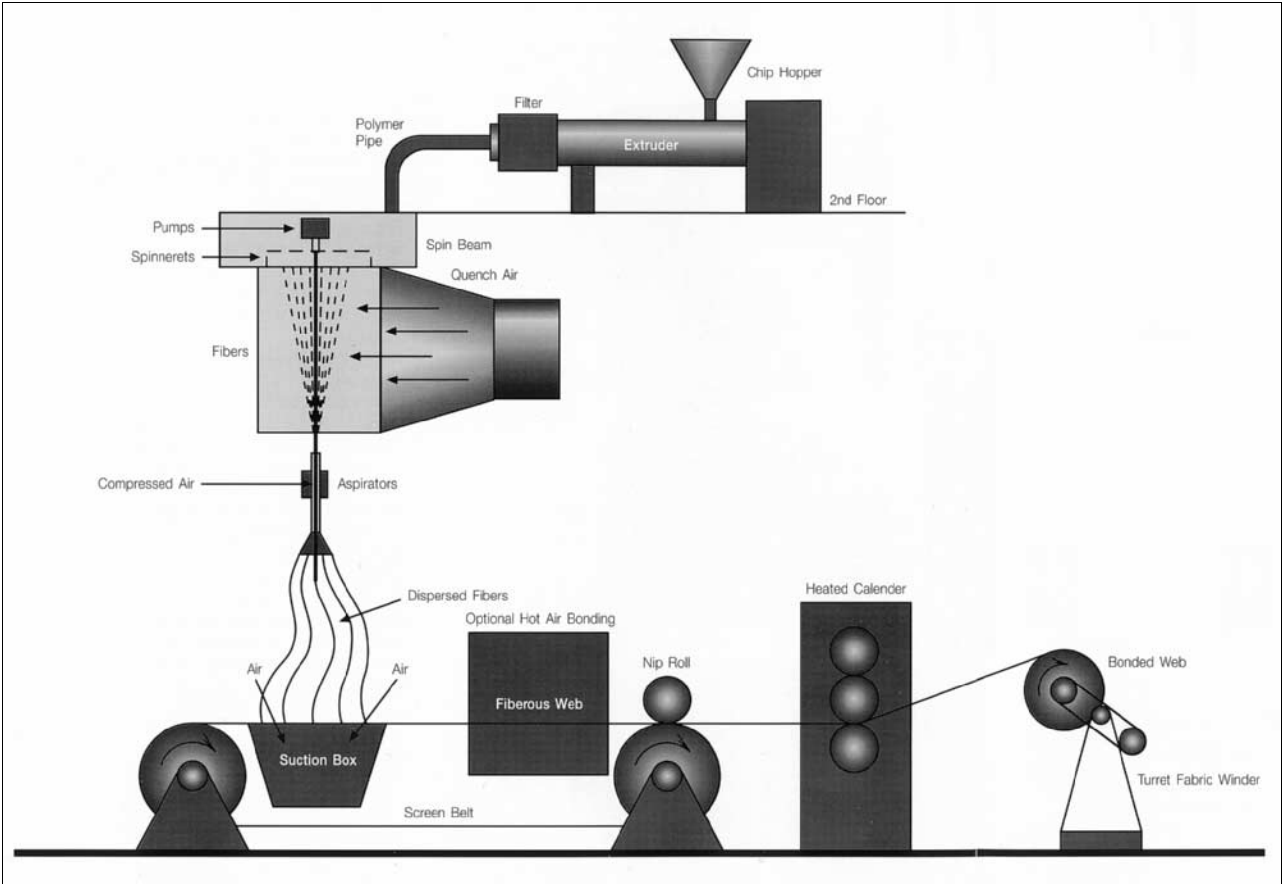


Figure 16.22 Typical spun bonded fiber extrusion line.

are available, particularly for use with hot aqueous solutions. Flame retardant grades cater to construction use. These are not acceptable for use with potable water but polypropylene is otherwise very suitable for this application and many grades conform to the requirements of the various water authorities. Polypropylene pipes are subject to degradation by ultra-violet light so UV stabilized grades should be used if the pipes are to be stored in the open for any length of time. This is particularly true for thin-walled pipes. The melt flow index for pipe grades is relatively low, typically ranging from 0.8 to 2.0 grams/ 10 min. Applications for polypropylene pipes include potable water supply, domestic waste systems, under-floor heating circuits, chemical effluent disposal systems, and thermal spring conduits.

16.1.6.1 Production

Dies for pipe production consist essentially of a female die ring that shapes the pipe outside diameter, and a male mandrel that shapes the inside diameter. The difficulty is to support the mandrel in rigid and accurate alignment with the die ring without compromising the product. The spider type (Figure 16.23) uses three or four spider legs to support the mandrel but these legs cause axial weld lines as the melt flows around them. An alternative is the breaker plate design in which the mandrel is supported by a disc pierced by a multitude of small holes. A better solution, particularly for larger pipe dies is the spiral mandrel. Here the mandrel is rigidly supported and the melt flow is directed around it in an initially helical pattern which is converted to axial flow by the geometry of the flow channels and lands. Weld lines

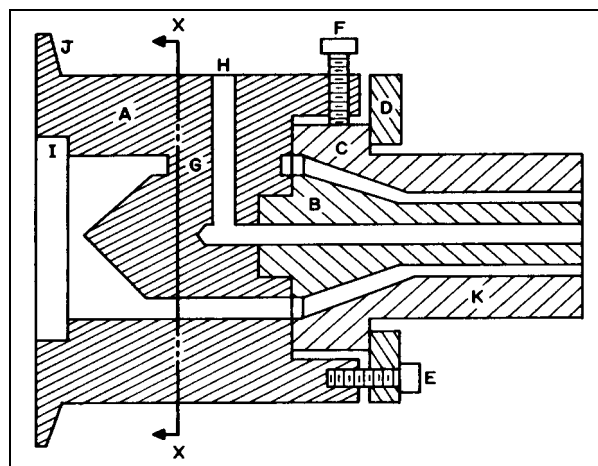


Figure 16.23 Typical spider-type tube die for pipe and tube extrusion. A-Die body, B-Mandrel, pin, male die part, C-Die, die bushing, female die part, D-Die retaining ring, E-Die retaining bolt, F-Die centering bolt, G-Spider leg, H-Air hole, I-Seat for breaker plate, J-Ring for attachment to extruder, K-Die land.

are eliminated but the difficulty is to ensure an even flow rate at all points of the die outlet. Polypropylene requires a long die land length to increase die pressure, minimize flow rate variations, and improve the weld line strength of spider-type dies. The length of the die land should be 14 to 25 times the wall thickness of the pipe.

The outside diameter of the pipe may be calibrated either by an internal air pressure of 1.3 to 2.0 bar, or by external calibration in a vacuum sizing tank (Figure 16.24) operating at a pressure of 0.3 to 0.5 bar. For calibration by internal pressure, the diameter of the die ring is made approximately equal to the internal diameter of the finished pipe. For vacuum tank calibration, the die ring is made up to 25% larger and the haul-off is set for a wall thickness draw-down of up to 30%.

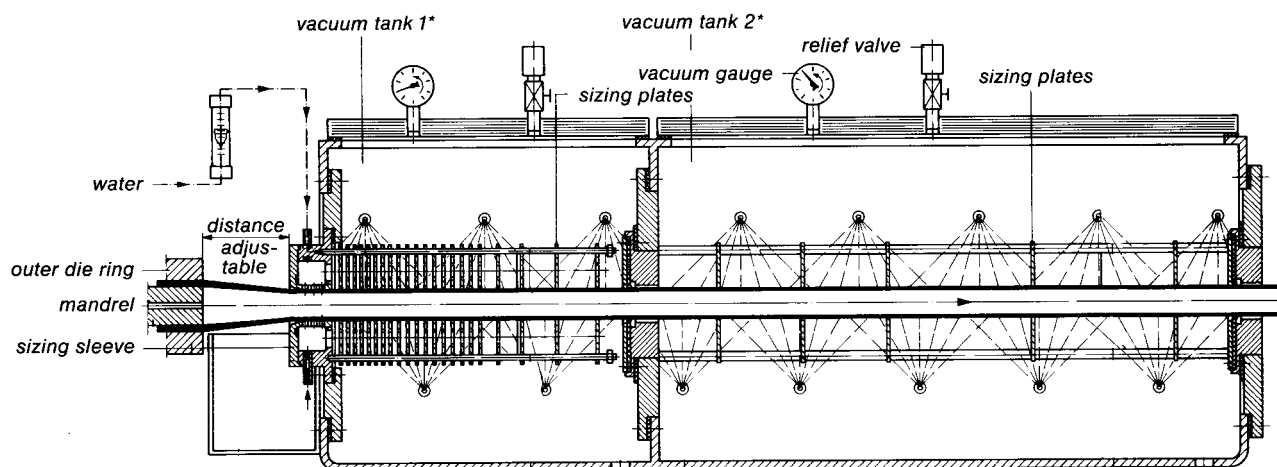


Figure 16.24 Vacuum sizing tank used for pipe and tube extrusion.

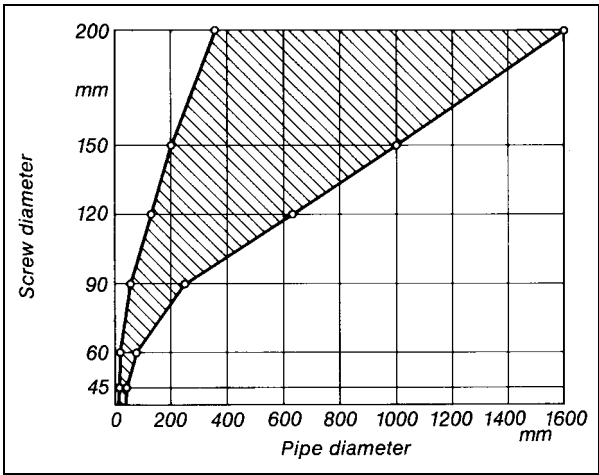


Figure 16.25 Recommended relationship between pipe diameter and screw diameter.

The match between die size and extruder size is inexact but certain limits should be observed in the interests of economical and consistent production. The chart (Figure 16.25) gives the recommended relationships for conventional single-screw extruders.

16.1.6.2 Pipe characteristics

Like other thermoplastics, polypropylene pipes creep when exposed to long term stress arising from internal pressure. The effect is more marked

at higher temperatures. Pipe creep is determined by long-term pressure tests at a range of temperatures. The resulting curves (Figure 16.26) can be used to establish a safe working stress for design purposes. The wall thickness necessary to withstand a given internal pressure can be calculated from the expression:

$$s = \frac{p}{10} \left(\frac{D}{2\sigma + \frac{p}{10}} \right)$$

where s = wall thickness (mm), p = internal pressure (bar), D = outside diameter of pipe, σ = safe working stress at the service temperature (N/mm^2).

A safety factor of 2 should be used when designing polypropylene pressure pipes, so a representative safe working stress at 20°C would be 5 N/mm^2 (Table 16.3). The table suggests representative design figures but the exact values are grade-specific and should always be confirmed before designs are finalized. The quoted figures are based on a design life of ten years or more. At higher temperatures, the design life must be shorter (Figure 16.26). Polypropylene under-floor heating pipes typically operate at about 40°C and temperatures should not exceed 65°C. Similarly, effluent waste pipes may operate intermittently at up to 80°C but sustained service should be limited to

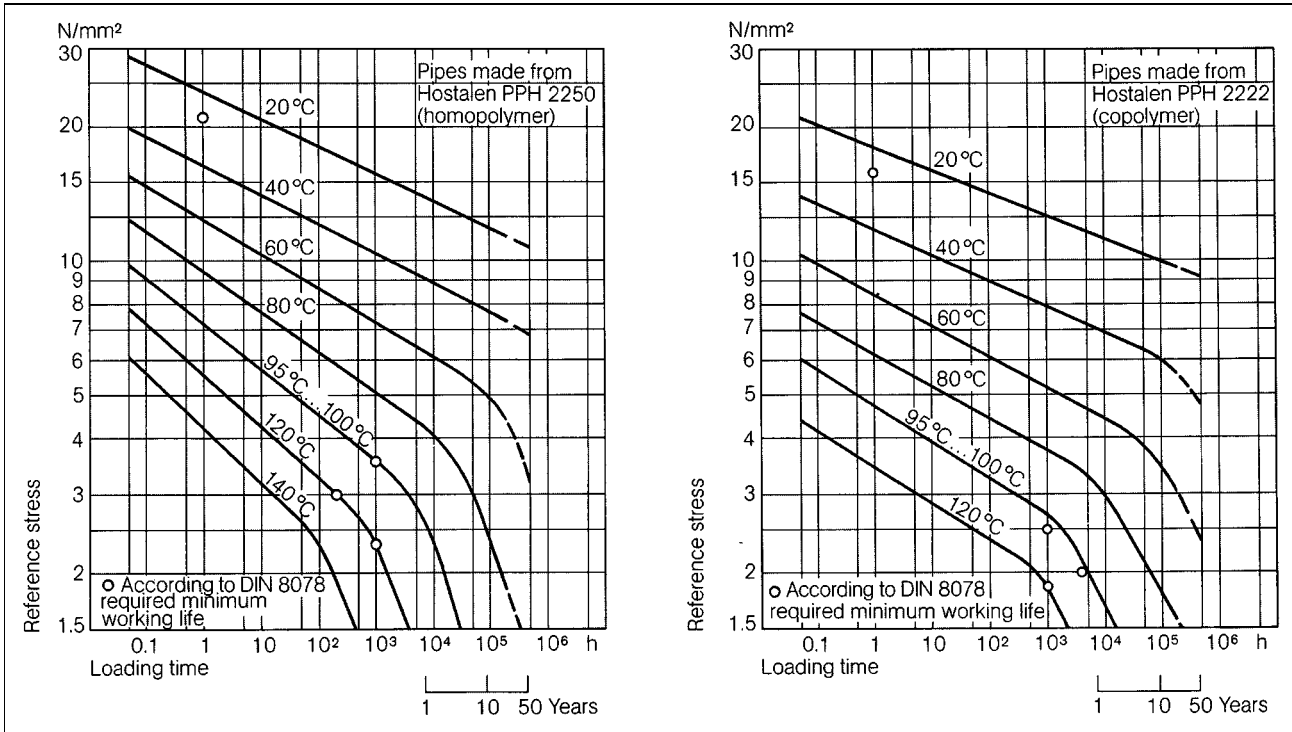


Figure 16.26 Creep rupture strength of pipes made from Hoechst Hostalen homopolymer (PPH 2250) and co-polymer (PPH 2222) polypropylene. The pressure medium is water.

Table 16.3 Suggested safe working stresses for polypropylene pipes. The quoted figures are based on a design life of ten years or more.

Service temperature (°C)	Safe working stress (N/mm ²)
20	5
40	3
60	1.6

60°C. The smallest recommended bending radius for polypropylene pipes such as under-floor heating ducts is 8 to 10 times the pipe diameter.

16.1.7 Coextrusion

Coextrusion is the process of forming an extrudate composed of more than one thermoplastic melt stream. The process came about because some service demands, particularly from the packaging industry, could not be satisfied by a single polymer although they could be met by a combination of polymers. Coextrusion was first practiced in the production of cast film and is now also used in blown film and sheet extrusion. The intention is normally to produce a laminar structure in which each layer contributes a key property to the overall product performance. Coextruded films may be very complex structures composed of many different functional layers and also including tie layers whose purpose is to bond neighboring layers of limited compatibility. Seven or more layers are not uncommon. However, side-by-side coextrusion is also possible. This process is used to produce decorative film and is also employed in profile extrusion, for example to provide a flexible seal along the edge of a rigid strip.

Separate extruders are required for each distinct material in the coextrusion. The process has two variants, depending on the point at which the separate melt streams are brought together. In feed

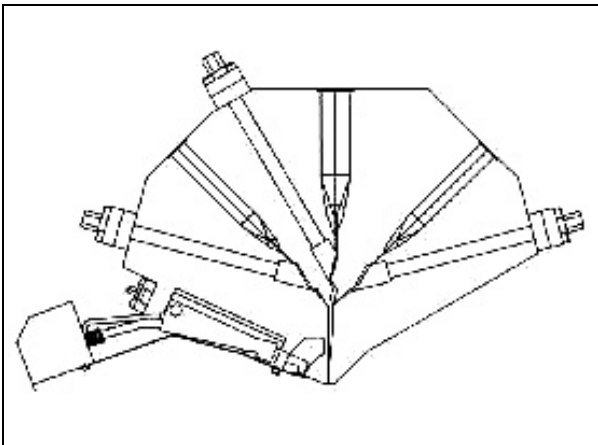


Figure 16.28 Three-layer multi-manifold coextrusion die.

block coextrusion, the streams are merged into a single laminar melt flow in a feed block (Figure 16.27) which is positioned immediately upstream of the extrusion die. The process depends on the high viscosity of plastics melts to prevent intermingling of the layers as they pass through the extrusion die. The flow rate of each component layer can be controlled by valves in the feedblock and the capital cost is relatively low. The alternative, die coextrusion, uses a complex die construction in which separate melt path manifolds are arranged to merge at a point close to the die exit (Figure 16.28). The thickness and flow rate of individual layers can be independently controlled, and it is also possible to handle polymers with substantially differing viscosities and melt temperatures. The capital and maintenance costs of such multi-manifold coextrusion dies are high.

References for chapter 16:
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 1064, 1076, 1078, 1106, 1130, 1132, 1181, 1203,
 1216, 1224

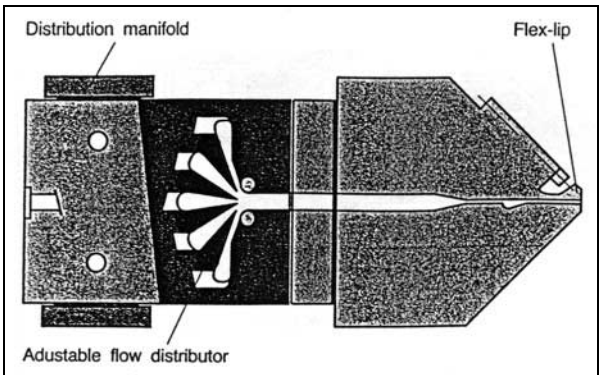


Figure 16.27 Schematic of coextrusion feedblock.

Introduction

About 2% of polypropylene consumption is converted into sheet (Figure 13.1). A proportion of this is used in die-cut and fabricated forms, so unless the reported figures are conflating some sheet production with that of film, thermoforming emerges as a minor conversion process for polypropylene. The physics of thermoforming are not unlike those of blow molding, and the reason for the slow take up of polypropylene in thermoforming is much the same as for blow molding (Section 15.1). The relatively low melt strength of polypropylene sheets leads to excessive sagging and thinning, so causing process difficulties. Furthermore, the high enthalpy of the material (Section 13.1.2) makes it difficult to heat and cool sheets evenly. But, as in blow molding, the situation is changing. Developments both in polypropylene materials and in the thermoforming process are making this a rapid growth area for polypropylene.

The light weight, high softening point, and oxygen barrier properties of thermoformed polypropylene are making inroads into food packaging, where the process is taking market share from thermoformed polystyrene and injection molded polypropylene. Polypropylene containers can be hot filled and microwaved, and the thermoformed version can have thinner walls than in injection

molding. Typical food applications include deli containers, cups for yogurt and other dairy products, ready meals trays, punnets, chocolate and confectionery packaging, and disposable cold drink cups. Other applications include blister packs and medical and pharmaceutical packaging. Packaging products are frequently and increasingly thermoformed from multi-layer coextruded sheet (Section 16.1.7) in which polypropylene provides the structural base but is augmented by barrier and tie layers.

17.1 Process basics

Thermoforming is a process for converting thermoplastics into shell forms, using sheet material as a preform. With the exceptions of matched mold (Section 17.3.10) and twin sheet (Section 17.3.11) thermoforming, the process uses an open mold that defines only one surface of the thermoformed part. The second surface is only indirectly defined by the mold and so will lack crisp definition of features to an extent dependent partly on the sheet thickness. There is no direct control over wall thickness of the formed part; this will vary from feature to feature according to the degree of stretch and thinning experienced at that point. Normally, it will be an aim in thermoforming to obtain as even a wall thickness

as possible in the finished part. Because the process uses a sheet preform and a single-surface mold, it is not possible to create independent features on the second surface. These considerations confine most thermoformed articles to relatively simple shapes.

At its most basic, thermoforming is performed by clamping a heated thermoplastic sheet over a mold cavity and drawing a vacuum in the cavity. This causes atmospheric air pressure to press and plastically deform the sheet into the mold cavity, where it is cooled to retain the formed shape. This is known as vacuum forming, a term that is less comprehensive than thermoforming, although the two are often erroneously treated as

Table 17.1 Principal options available in the thermoforming process

Process Factor	Options
Forming force	Vacuum Positive air pressure Power press
Mold type	Female Male Matched female/male
Sheet pre-stretch	Vacuum Positive air pressure (billow) Mechanical plug
Material input	Extruder (in-line, hot forming) Reel (reheat, cold forming) Cut sheet (reheat, cold forming)
Process phase	Solid phase Melt phase
Heating mode	One side of sheet Both sides of sheet (sandwich)
Heating means	Radiation: rod, ceramic, quartz or infra-red heaters Convection: hot air oven Conduction: hot roller, contact panel or hot oil bath

Table 17.2 Principal thermoforming processes

Process	Forming force	Mold type	Sheet pre-stretch
Basic vacuum	Vacuum	Female	None
Basic pressure	Positive air pressure	Female	None
Drape	Vacuum	Male	None
Snap back	Vacuum	Male	Vacuum
Billow	Vacuum	Male	Positive air pressure
Plug assist	Vacuum	Female	Mechanical plug
Billow plug assist	Vacuum	Female	Positive air pressure and mechanical plug
Air slip	Vacuum	Male	Positive air pressure
Air slip plug assist	Vacuum	Male	Positive air pressure and mechanical plug
Matched mold	Power press	Matched male/female	None
Twin sheet	Positive air pressure	Matched female/female	None

interchangeable and synonymous. In practice, the key factors in thermoforming all have two or three optional forms (Table 17.1). For example, the forming force can be supplied by vacuum, by positive air pressure, or by a power press. These options can be assembled in many different permutations to create a very wide variety of thermoforming processes. In this chapter, we discuss the main factors (Section 17.2) and the principal processes (Table 17.2).

17.2 Process factors

The principal factors in the thermoforming process are the forming force, mold type, method of pre-stretching the sheet, the material input form, and the process phase condition. These factors have a critical influence on the appearance, quality and performance of the thermoformed part.

17.2.1 Forming force

Thermoforming is essentially a low pressure process, in which the forming force is generated either by vacuum or positive air pressure or by a combination of both. However, in the special case of matched mold thermoforming, the force is supplied by a power press and may be much greater.

In vacuum forming, the heated sheet forms part of a closed cell together with the mold. When the air in this cell is evacuated, atmospheric pressure forces the sheet into contact with the mold. The force so generated clearly cannot exceed atmospheric pressure and in practice is rather less because of the difficulty of creating a perfect vacuum in the mold/sheet cell. A vacuum of 85% to

90% of theoretical maximum is more likely and this will generate a forming force not greater than about 90 kPa (13 psi).

Pressure, particularly in the low pressure range used in thermoforming, may be expressed not only in a wide variety of units but also by two systems of measurement, namely gauge pressure and absolute pressure. Gauge pressure takes atmospheric pressure as the datum or zero point, while zero pressure is the datum for absolute pressure measurements. In other words, absolute pressure values exceed gauge pressure values by a quantity equal to atmospheric pressure. The distinction is sometimes made clear by adding a suffix to the unit of pressure so that, for example, psia and psig refer respectively to absolute and gauge pressures expressed in pounds force per square inch. The table (Table 17.3) compares absolute and gauge values for some common units of pressure.

Pressure forming overcomes the force limitations of vacuum forming by applying air under pressure on the non-mold side of the sheet in place of a vacuum on the mold side. The sheet is forced into contact with the mold at pressures greater than atmospheric, and this necessitates venting any air that is trapped between the sheet and the mold. Venting may be provided by simple passages communicating with atmosphere but is often effected by employing a vacuum on the mold side of the sheet. In this case, the venting vacuum increases the forming force by an increment approaching one atmosphere. Industrial compressed air supply systems normally operate at about 550 kPa to 710 kPa (80 psi to 100 psi) and this pressure may be sufficient for many applications.

Table 17.3 Comparison of pressure scales for thermoforming. Absolute pressure is expressed with zero pressure as the datum; gauge pressure takes atmospheric pressure as the datum.

Atmospheres gauge	Bar absolute	Bar gauge	kPa absolute	kPa gauge	kgf/cm ² absolute	kgf/cm ² gauge	Psi absolute	Psi gauge
-1.00	0.00	-1.01	0.00	-101.33	0.00	-1.03	0.00	-14.70
-0.90	0.10	-0.91	10.13	-91.19	0.10	-0.93	1.47	-13.23
-0.85	0.15	-0.86	15.20	-86.13	0.15	-0.88	2.20	-12.49
-0.50	0.51	-0.51	50.66	-50.66	0.52	-0.52	7.35	-7.35
0.00	1.01	0.00	101.33	0.00	1.03	0.00	14.70	0.00
0.50	1.52	0.51	151.99	50.66	1.55	0.52	22.04	7.35
1.00	2.03	1.01	202.65	101.33	2.07	1.03	29.39	14.70
1.50	2.53	1.52	253.31	151.99	2.58	1.55	36.74	22.04
2.00	3.04	2.03	303.98	202.65	3.10	2.07	44.09	29.39
3.00	4.05	3.04	405.30	303.98	4.13	3.10	58.78	44.09
4.00	5.07	4.05	506.63	405.30	5.17	4.13	73.48	58.78
5.00	6.08	5.07	607.95	506.63	6.20	5.17	88.18	73.48
6.00	7.09	6.08	709.28	607.95	7.23	6.20	102.87	88.18
7.00	8.11	7.09	810.60	709.28	8.27	7.23	117.57	102.87
8.00	9.12	8.11	911.93	810.60	9.30	8.27	132.26	117.57
9.00	10.13	9.12	1013.25	911.93	10.33	9.30	146.96	132.26
10.00	11.15	10.13	1114.58	1013.25	11.37	10.33	161.66	146.96
15.00	16.21	15.20	1621.21	1519.88	16.53	15.50	235.14	220.44
20.00	21.28	20.27	2127.83	2026.51	21.70	20.66	308.62	293.92
25.00	26.34	25.33	2634.46	2533.13	26.86	25.83	382.10	367.40
30.00	31.41	30.40	3141.09	3039.76	32.03	31.00	455.58	440.88
35.00	36.48	35.46	3647.71	3546.39	37.20	36.16	529.06	514.36
40.00	41.54	40.53	4154.34	4053.02	42.36	41.33	602.54	587.84

However, pressure thermoforming equipment typically operates at pressures up to about 2500 kPa (360 psi), while pressures as high as 3447 kPa (500 psi) have been reported. These pressures of course are still very low when compared to those commonly used for injection molding or extrusion.

The forming force in matched mold forming is supplied by a power press and so, in principle, is almost unlimited. In practice, the force is limited by the economics of mold construction as well as the needs of the process and is usually in the range 1.5 MPa to 4 MPa (218 psi to 580 psi).

17.2.2 Mold type

Thermoforming is a shell process performed in an open mold that defines only one surface of the product. Definition of the second surface is indirect and imprecise. This has a direct bearing on the mold

which must be so designed that it directly defines the more important of the product's two surfaces. Product geometries are limited to forms attainable by a deformed sheet and consist mainly of recesses and projections orthogonal to and arranged on either side of the plane of the sheet preform. This makes it convenient and reasonably accurate to classify thermoforming molds as female or male.

The female mold consists of a recessed cavity or cavities formed in a mold block. This is the most common mold form because it is easy to clamp the heated sheet across the unobstructed mold face. The resulting product has a clearly defined male form and an imprecise female form. Often the simplicity of the female mold outweighs the cosmetic requirements of the product, so that it is common to see packaging products such as nest-

type box liners in which the recessed presentation face is the imprecise second surface.

The male mold consists of a form or punch projecting from a mold block. The punch interferes with the plane of the sheet preform so sheet clamping must take place outside the mold. Subsequently, the sheet is moved into contact with the mold, so the penalty for using a male mold is an increase in the mechanical complication of the process. The resulting product has a clearly defined female form and an imprecise male form.

The third mold type used in thermoforming is the matched mold. Exceptionally for thermoforming, this is a closed mold consisting of two halves, each defining one surface of the finished article. The matched mold is similar in concept to a compression mold but the cavity geometries remain limited to shapes attainable by a sheet preform.

17.2.3 Sheet pre-stretch

It is often advantageous in thermoforming to pre-stretch the heated sheet immediately prior to forming it in the mold. There are two principal reasons for this. First, particularly when simple vacuum forming is combined with solid phase forming, the available force may be insufficient to stretch and form the sheet efficiently. A second reason is that some shapes, for example cup or box forms of relatively high aspect ratio, give rise to excessive variations in wall thickness when formed without pre-stretch. This arises because the sheet touches down first on the edges and side walls of the mold cavity and then perhaps in the center of the base. The combined mechanisms of chilling and friction tend to anchor the sheet in these positions so that all the remaining deformation needed to complete the forming is contributed by a minor proportion of the sheet area. In this case, the remedy is selective pre-stretching in a manner related to the geometry of the mold form.

Selective pre-stretching is achieved by means of specially shaped plugs which are mechanically advanced into the heated sheet to produce local stretching in a way calculated to counteract the thinning tendency imposed by the mold geometry. The technique is generally referred to as plug assist. The plug shape exerts a considerable influence on wall thickness variation (Figure 17.1), and plug design is as much an art as a science. A blunt-nosed plug tends to produce articles with a thick base and thinner sidewalls. Tapered can-like plugs, on the other hand, produce a forming with thicker

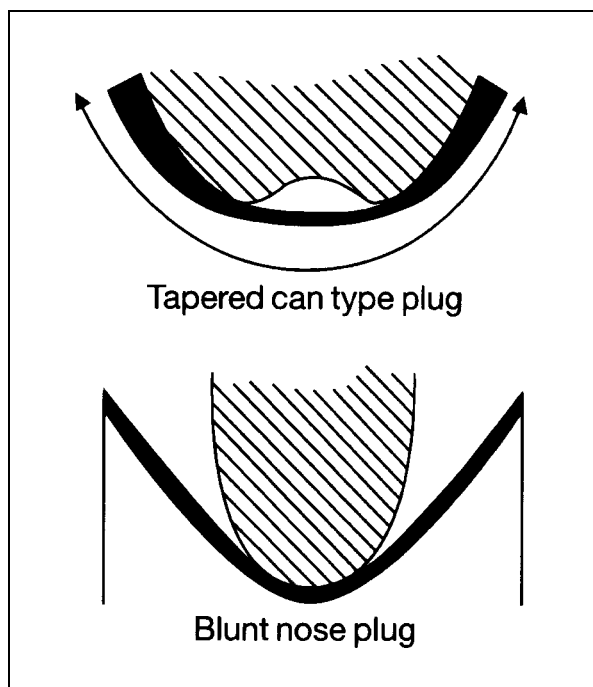


Figure 17.1 Influence of plug profile on sheet thinning.

and stronger corners. Plug design must be optimized for each individual application but the general rule is for smooth surfaces and blended shapes without sharp transitions in form. The coefficient of friction for heated polypropylene sheet is relatively high, so plugs should be made from low-friction materials. The usual choices are polyamide, PTFE, or filled epoxy resins.

The sequencing of the plug pre-stretch also influences the wall thickness distribution of the thermoformed part. The plug should contact the sheet virtually at the moment it is clamped against the mold. If contact is made before clamping, the stretching will not be sufficiently selective and localized, and there may even be a tendency to crease or puncture the sheet. On the other hand, the sheet will cool quite rapidly after clamping so if plug contact is delayed, material thickness distribution will be adversely affected. Plug speed is also significant. A high-speed plug pre-stretch will result in highly oriented sidewalls, but the wall thickness distribution will suffer because too much sheet material will be drawn to the bottom of the mold cavity. The imbalance can be observed by measuring the crush resistance performance of thermoformed containers (Figure 17.2).

When the sheet pre-stretch is to be generalized over the whole sheet rather than localized in the area of individual mold features, the effect is achieved either by partial vacuum or positive air

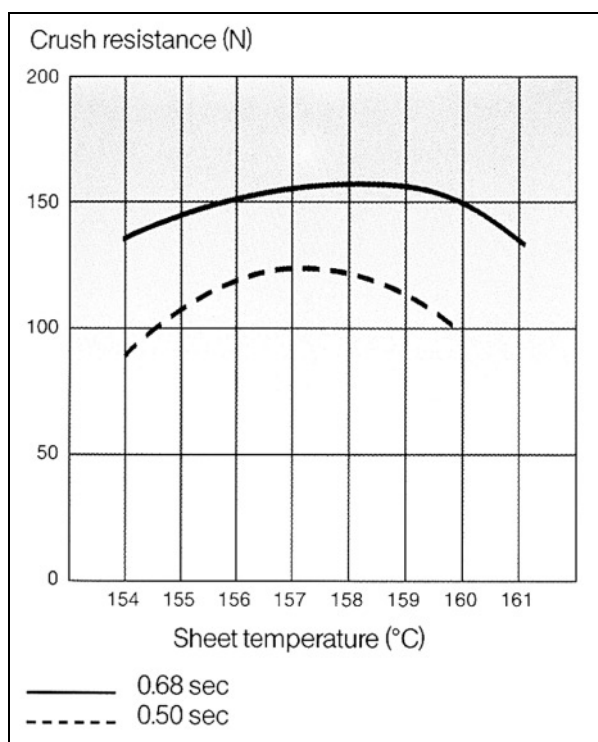


Figure 17.2 Effect of plug pre-stretch timing on the crush resistance of cups thermoformed from Fina-pro PPH 4042 S polypropylene homopolymer.

pressure. In both cases, a low pressure differential and a controlled flow rate is employed to inflate the sheet without causing excessive thinning or rupture. Pre-stretch by positive air pressure is often referred to as billow. The air pressure is sometimes generated by the piston effect, produced by advancing a mold towards the sheet. This pre-stretch technique is generally known as air slip. Some processes combine plug and billow pre-stretch techniques.

All forms of pre-stretch tend to modify orientation in the formed part. When forming is performed without pre-stretch, the orientation depends very much on the mold form geometry. Clearly, the situation is complex, but the tendency is for uniaxial orientation to predominate in the product sidewalls, while biaxial orientation is prevalent in regions that remain substantially parallel to the plane of the original sheet. These patterns are superimposed on whatever residual orientation remains in the sheet after heating. Pre-stretch changes the picture somewhat. The billow process imposes an overall biaxial orientation on the sheet which is later modified by the forming process. Plug pre-stretch, on the other hand, tends to emphasize the orientation patterns arising from forming.

17.2.4 Material input

The raw material for thermoforming is a thermoplastics material in sheet form. The sheet is produced by extrusion (Section 16.2.4) and can either pass directly from the extruder to the thermoformer or can pass through an intermediate storage phase. During storage, the sheet is held at room temperature and must be completely reheated before forming, so this two-stage process is known as reheat forming or cold forming. The alternative single-stage process is known as in-line forming or hot forming.

Reheat forming is the most widely practiced process. Thermoforming is entirely separated from sheet production, which can thus be left in the hands of specialists. The capital cost of equipment is lower and the process is easily switched between different materials and sheet sizes. Material input for reheat forming is either in the form of bulk reeled sheet or as cut sheets; the choice depends mainly on the sheet thickness.

In-line forming integrates thermoforming with sheet production, and the two must proceed at synchronized rates. The alternative name of hot forming is something of a misnomer because the extruded sheet reaches the thermoformer with only residual heat remaining after passing through chilling and polishing rolls. Reheating is necessary before forming can take place but there is some saving in heat input and heat history, and the sheet line can be controlled to produce a degree of crystallinity favorable to the product to be thermoformed. Heating through the sheet thickness is more uniform than that achieved by the reheat process, so the stress levels in formed containers are lower, and the resistance to distortion under hot-filling or microwaving is better. The in-line process eliminates sheet wind-up and stacking stations, sheet inventories, and the associated handling. It also removes the risk of post-extrusion crystallization on the reel. Process scrap can be returned directly to the extruder, but the process is relatively inflexible and is best suited to very long production runs and dedicated product lines. The in-line process is gaining ground in the conversion of polypropylene, particularly for food and dairy product packaging.

17.2.5 Process phase

There are two distinct process strategies for thermoforming polypropylene. As a semi-crystalline material it can be processed either below or above

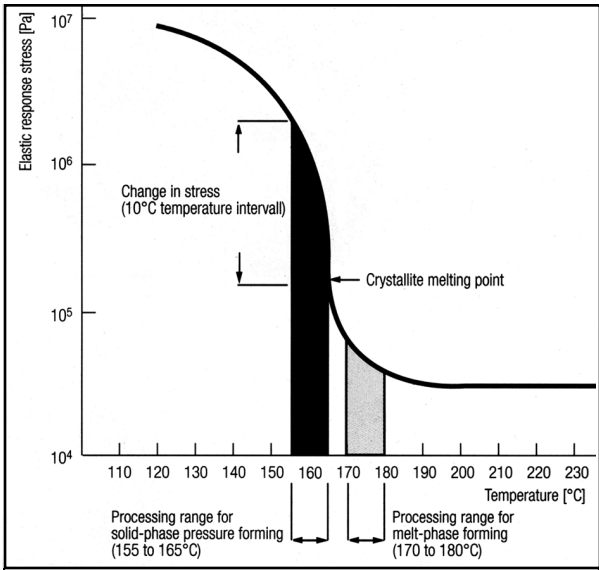


Figure 17.3 Process phases for thermoforming polypropylene.

the crystalline melting point (Figure 17.3). When forming is carried out below the crystalline melting point, it is known as solid phase forming; melt phase forming is performed at temperatures above the crystalline melting point.

Solid phase forming of polypropylene is carried out at temperatures ranging from 155°C to 165°C; the range mid-point is usually quoted as the optimum setting. Under these conditions the sheet is relatively strong and resistant to sagging. The disadvantage is that a simple vacuum may be insufficient to form the sheet fully, so plug assistance is advisable to pre-stretch the sheet. The magnitude of force needed to form the sheet in the solid phase is markedly dependent on temperature, and even within the narrow recommended working range may vary by an order of magnitude. Solid phase forming is effective with all thermoforming grades of polypropylene.

Melt phase thermoforming is performed at temperatures ranging from 170°C to 180°C and requires polypropylene grades with a high melt

strength. Conventional grades have insufficient sag resistance to be formed successfully by this method. Sag resistance is related to molecular weight and molecular weight distribution and is expressed by the extensional viscosity of the material. High melt strength thermoforming grades are formulated to optimize these characteristics, generally using long-chain branching to impart the necessary behavior.

The two techniques result in products with rather different characteristics (Table 17.4). Melt phase thermoforming requires less force and so generates lower residual stress levels in the finished part. The lower tensile strength of the sheet during forming also tends to produce a more even thinning and therefore reduces wall thickness variations. However, heating above the crystalline melting point produces an amorphous sheet structure, which re-crystallizes during cooling to produce a forming with decreased transparency but better heat resistance. Performance under heating also benefits from the lower stress level, which results in a reduced tendency for distortion and reversion to the original sheet form. For this reason, melt phase thermoforming is often preferred for retortable and microwaveable polypropylene containers. However, modern solid phase thermoforming can also produce containers capable of service under these conditions, particularly when carried out with multilayer coextruded film and sheet.

17.2.6 Heating

The heating process is of critical importance in thermoforming, both economically and technically. Heating accounts for some 80% of the total energy demand in thermoforming, so heating efficiency exerts a profound influence on process economics. Technically, the heating system must satisfy exacting demands. Heat can be transferred to the sheet only through its outside surfaces, but forming quality and consistency require uniform heating throughout the sheet thickness and at its core. This is particularly difficult to achieve with polypropylene,

characterized as it is by high enthalpy and low thermal conductivity. Additionally, and particularly for polypropylene, the process temperature window may be very narrow, requiring precise temperature control linked to and proportional with sheet throughput rates.

Table 17.4 Comparison of product characteristics between solid phase and melt phase forming

Property	Solid phase forming	Melt phase forming
Wall thickness distribution		More even
Residual stress		Lower
Optical properties	Clearer	
Mechanical properties	Stronger	
Heat resistance		Greater

Heating is performed by radiation, convection or conduction means. When radiation or conduction is used, there is the option to apply heat either to one or both surfaces of the sheet. In the case of convection, both sides of the sheet will be heated. Given the difficulty of heating the sheet core uniformly, it is preferable to heat both surfaces of the sheet. The upper limit of sheet thickness for effective single-sided heating is about 1mm.

Infra-red radiant heating is now the most widely used means of sheet heating for reel-fed or in-line thermoforming machines. The heaters are normally arranged in a heating tunnel in a series of independently controlled zones that gradually increase the sheet temperature first to a stress relaxation temperature of about 120°C, then to the forming temperature. To counteract sagging in polypropylene sheet, the final heating to the forming temperature should be as rapid as possible without compromising temperature uniformity throughout the sheet thickness. Some thermoformers use a sheet conveyor system similar to a tenter chain (Section 16.2.2.3.2) in order to counteract sagging by tensioning the sheet. Such systems are equipped with independent edge heating zones to compensate for the heat sink effect of the conveyor. Alternatively, hot air ovens may also be used to heat the sheet by convection but it is more difficult to arrange for distinct and progressive zones of temperature control.

Different arrangements are necessary for cut sheet machines. In this case it is usual to pre-heat sheets by convection in static ovens, followed by final heating of both surfaces in a radiant sandwich heater operating close to the mold. Conduction may also be used for sheet heating and particularly for pre-heating, either in the form of heated rolls or as a flat contact plate that the sheet passes over. Hot immersion baths filled with a heat transfer oil or other suitable fluid can also be used for sheet heating, but these introduce practical operational difficulties and are not widely employed.

The thermoforming temperature for polypropylene sheet depends on whether solid phase or melt phase forming is being practiced (Section 17.2.5); in either case, the recommended process window covers a temperature range of only 10°C. In solid phase forming, the force required to form the sheet varies greatly within the recommended temperature range (Figure 17.3); the variation is much smaller in melt phase forming. When forming is performed at temperatures towards the lower end of the solid phase range, the article will have a

higher degree of orientation and improved transparency, but it will have a less uniform distribution of wall thickness when compared to one made at the higher end of the range. These variations combine to affect the product crush resistance in a complex manner. For example, wall thickness variations decrease crush resistance while orientation increases it. This means that optimum settings depend to an extent on individual product geometries and any generalizations must be approached with care. Nevertheless, the graph (Figure 17.4) illustrates that very small variations in sheet temperature can have a marked effect on the properties of the finished part and confirms the importance of precise temperature control when thermoforming polypropylene.

17.3 Thermoforming Processes

The options available for the principal process factors can be combined in different ways to produce an almost infinite variety of thermoforming processes, and indeed some thermoforming machines are designed to adapt to a number of different processes. Others, particularly those designed for high production rates and long product runs, are dedicated to a specific process. Here we outline the most common variants of the thermoforming process.

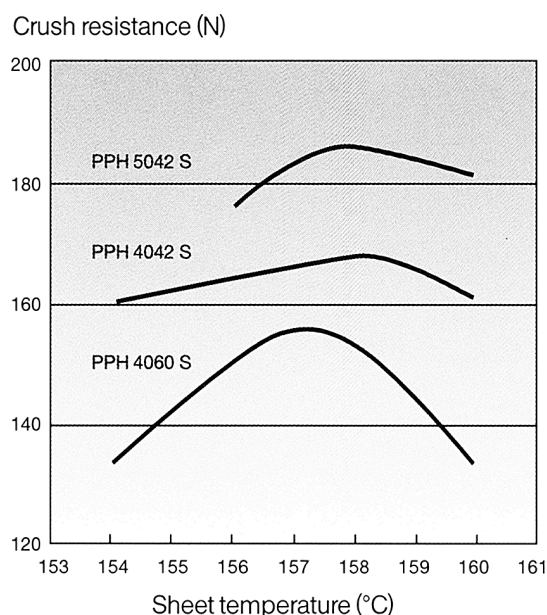


Figure 17.4 Effect of sheet forming temperature on the crush resistance of cups thermoformed from Fina-pro polypropylenes. Key: PPH 5042 S = nucleated homopolymer with narrow molecular weight distribution and anti-static protection (MFI 6.0), PPH 4042 S = nucleated homopolymer with antistatic protection (MFI 3.0), PPH 4060 S = general purpose homopolymer (MFI 3.0)

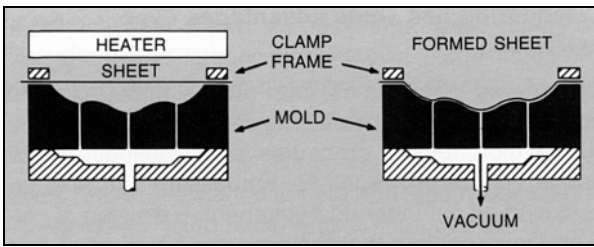


Figure 17.5 Basic vacuum forming process.

17.3.1 Basic vacuum forming

Basic vacuum forming is the simplest of the thermoforming processes. A female mold is used, with an unencumbered planar upper surface against which the sheet is clamped (Figure 17.5). The sheet is first gripped around its periphery in a frame clamp and is then heated to the final forming temperature, preferably in a sandwich heater that heats both surfaces of the sheet. The frame is then lowered to contact and seal against the mold face where together with the mold cavity it forms a closed cell. The mold is provided with a series of small ports through which the air in this cell can be evacuated by a switchable connection to a vacuum pump, usually augmented by a vacuum surge tank. The vacuum in the mold cavity causes atmospheric pressure to force the heated sheet into contact with the cooled mold cavity where it cools in the shape determined by the cavity. It is a characteristic of thermoforming that the product is formed within a region of waste sheet material arising from the peripheral clamped areas and from points between the cavities of multi-cavity molds. The product is completed by trimming away this waste material. The basic vacuum forming process is the foundation on which more flexible and elaborate thermoforming processes are built by adding elements such as billow and plug pre-stretching of the sheet.

17.3.2 Basic pressure forming

The basic pressure forming process is conceptually similar to vacuum forming. It uses positive air pressure instead of a vacuum to form the sheet and therefore overcomes the force ceiling of one atmosphere, which is a limitation of vacuum forming. The sheet is frame clamped and heated in the same way as for vacuum forming, but is then trapped and sealed between the mold and a pressure chamber (Figure 17.6). When air under pressure is admitted to this chamber, the sheet is forced into contact with the mold form. During this operation, air must be expelled from the space between the sheet and the

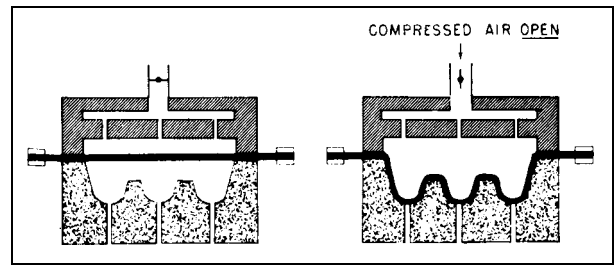


Figure 17.6 Basic pressure forming process.

mold form. This is done either by venting the space to atmosphere through a series of small ports in the mold or by evacuating the space by vacuum means. In the latter case, the vacuum increases the forming force but its primary purpose is as a venting device. It is convenient to use a vacuum in dual-purpose thermoforming machines designed to operate both the vacuum and pressure forming processes. Most of the process variations available to vacuum forming can also be incorporated in the pressure forming process, so adding further to the scope available to the thermoformer.

By exerting forming forces far in excess of atmospheric pressure, pressure forming processes greatly expand the design envelope and market applications for thermoforming. Much thicker and stronger sheets can be formed, the replication of mold surface detail is greatly improved, and it becomes possible to form relatively sharp corners and undercut features.

17.3.3 Drape

Drape forming is the simplest technique for use with a male mold. The heated clamped sheet is lowered over the mold until it seals with the planar mold base (Figure 17.7). The forming is then completed by drawing a vacuum through ports in the mold. The male mold form acts as a crude sheet pre-stretch plug, but the sheet chills rapidly on contact with the mold and there is a marked tendency for the process to produce thick bases and excessively thin side walls.

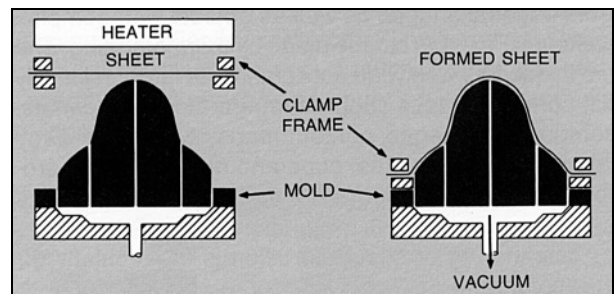


Figure 17.7 Drape forming process.

17.3.4 Snap back

Sheet pre-stretch is used when the forming force supplied by air pressure differential is insufficient to stretch the sheet adequately or when the forming force alone is likely to lead to excessive variations in the product wall thickness. The two cases overlap to an extent; however, broadly speaking, the first case is met by billow and air slip techniques that stretch the whole sheet, while the latter is dealt with by plug assist means that provide selective pre-stretching.

In the snap back process, a vacuum is used both to billow pre-stretch and to form the sheet. The heated sheet is first clamped across a vacuum box or chamber, which is then partially evacuated, causing atmospheric pressure to billow and stretch the sheet. A male mold is then advanced into the billowed sheet, and forming is completed by drawing a vacuum on the mold whilst venting the vacuum chamber to the atmosphere. The process resembles drape forming but with the advantage of sheet pre-stretch, which produces a much more uniform distribution of wall thickness.

17.3.5 Billow

Like the snap back process, billow forming is a sheet pre-stretch process used with a male mold. In this case, the sheet is clamped across a pressure chamber and is billow pre-stretched by applying a low magnitude positive air pressure to the chamber (Figure 17.8). The male mold is then moved into the

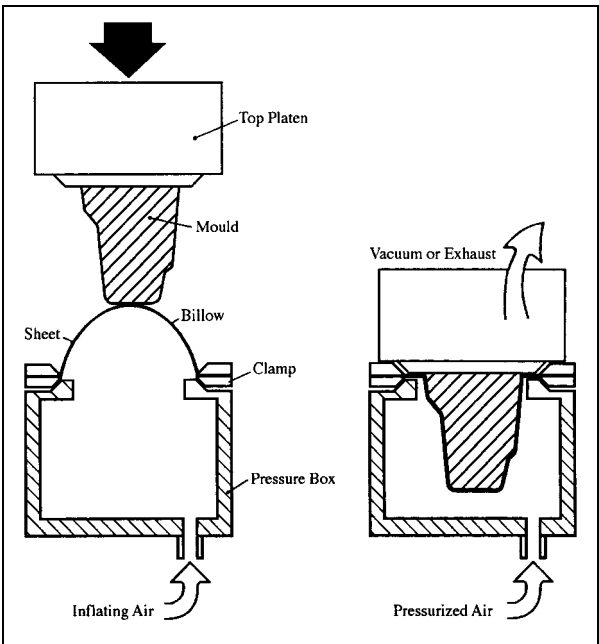


Figure 17.8 Billow forming process.

stretched sheet until the clamp seals on the mold periphery. Contact between the mold and the sheet can be regulated by controlling the rate at which the pressure chamber is vented to compensate for the advancing mold. The forming is completed by drawing a vacuum through ports in the mold. Alternatively, forming can be effected by re-pressurizing the pressure chamber at a higher pressure, or vacuum and pressure can be used together. The billow process has the advantage that a greater pre-stretch force is available than is the case with the snap back process.

17.3.6 Plug assist

Plug assist is used principally when the basic process is likely to lead to undue variations in the product wall thickness. Plug assist supplies essentially a selective or localized stretch which is related to the specific demands of an individual mold cavity. It is likely to be beneficial when the draw ratio — the ratio of depth to projected area — of a product feature is high, and when the product includes edges, corners and other features where excessive stretch and thinning is likely to occur. Plug assist is preferred for polypropylene sheet formed in the solid phase.

In the plug assist process, the heated sheet is clamped normally against the mold face, then one or more specially shaped plugs are advanced into the sheet to stretch it selectively in areas at least partly confined to the plug contact areas (Figure 17.9). In a large mold, there may be a number of different plugs specifically designed for different features in the mold. A multi-cavity mold for cups or packaging containers will be provided with a plug for each cavity. As the plug begins to enter the sheet, there may be additional pre-stretch derived from a billow effect around the plug. This is caused by air displaced from the closed cell formed by the sheet and mold and is absent if the cell is vented during the plug assist action. When

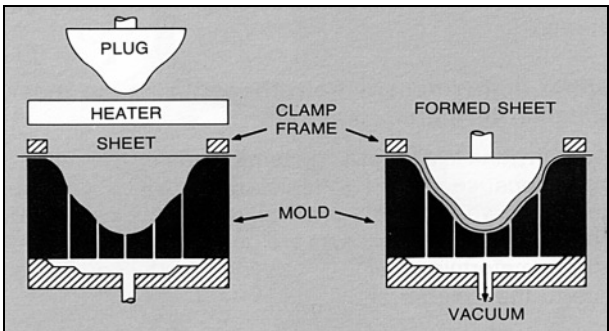


Figure 17.9 Basic plug assist process.

the plug is fully advanced, the forming is made by forcing the pre-stretched sheet into contact with the mold by the normal vacuum means. The plug assist technique is also frequently used with the pressure forming process.

17.3.7 Billow plug assist

A generalized sheet pre-stretch is combined with a further selective pre-stretch in the billow plug assist process. The clamped and heated sheet is first given an overall pre-stretch by inflating it with air at a low positive pressure before the plug is advanced to perform a selective stretch. The forming is then completed by drawing a vacuum through the mold in the normal manner. The process results in products with a good uniformity of wall thickness even at high draw ratios.

17.3.8 Air slip

The air slip process uses a positive pressure billow sheet pre-stretch that is generated by the movement of a male mold towards the heated sheet that is clamped across a pressure chamber. The mold platen acts as a piston in the chamber and drives a volume of air ahead of it that serves to billow the sheet. At the full extent of its forward travel, the mold periphery seals against the sheet frame, and forming is completed by drawing a vacuum through ports in the mold. Conceptually, the process resembles the billow process. The billow can be regulated to an extent by venting air from the pressure chamber, but the penalty for combining the billow and mold functions is a loss of fine control over individual parameters.

17.3.9 Air slip plug assist

Air slip techniques can be combined with plug assist for instances where the forming requires both generalized and selective pre-stretching of the sheet. In this case, a plug is advanced into the billowed sheet when the mold is at or near the full extent of its forward travel. A partial venting of the pressure chamber compensates in a controlled manner for the volume displaced by the advancing plug. When the plug pre-stretch is fully extended, the forming is completed by drawing a vacuum through ports in the mold. The process is particularly suitable for molds that have both male and female features.

17.3.10 Matched mold forming

Matched mold forming is a special case of thermoforming that differs from the mainstream in two

important respects. The mold defines both surfaces of the finished article, and the forming force is not supplied by air pressure differential across the sheet but by reaction forces generated by a power press acting on the mold. The process amounts to compression molding using a sheet preform. The mold form is reproduced on both halves of the mold, offset by a dimension equal to the sheet thickness; hence the term matched mold forming. The process is performed by clamping and heating the sheet in the usual way, then trapping it under pressure between the closing mold halves. High forming pressures allow thick sheets to be shaped with sharply defined detail on both surfaces. Mold costs are higher than for pressure forming, and undercuts can only be produced by introducing moving members into the mold.

17.3.11 Twin sheet forming

Twin sheet forming, sometimes known as dual sheet forming, is another special instance of thermoforming. The process resembles blow molding, except that twin heated sheets are used instead of a tubular parison. Like a blow mold, the twin sheet forming mold consists of matched halves, generally both female and equipped with pinch-off zones at the periphery of the cavities. A blowing needle is introduced at a suitable point between the sheets, then the mold halves are closed under pressure, welding the sheets into a closed body at the pinch-off zones. At the same time, air under pressure is introduced within the body through the blowing needle, forcing each sheet into conformity with the corresponding mold face. The scope for a high blowing pressure permits the use of thick sheets and provides good replication of mold detail. The process can be an economical way of producing large components such as pallets and tote trays.

17.3.12 Trimming

Because they are formed from a clamped sheet, virtually all thermoformed articles must be completed by trimming away the excess sheet material. For a single-impression mold, the operation consists of a single peripheral cut. In the case of a multi-impression mold, it is necessary to make individual cuts to sever the products from a web of waste material. Trimming is usually performed as a secondary operation, either in-line or off-line; however, for large volume applications, there is an increasing tendency to integrate trimming into the forming mold. The technique is sometimes known

as trim-in-place and is particularly advantageous for polypropylene formings.

Cut sheet feed machines are generally not equipped with in-line trimming, so it is normal to trim the products off-line. Such products tend to be bigger, more irregular in shape, and to be formed from thicker sheet than products from web-fed thermoformers. Taking the process off line makes it possible to choose the most suitable trimming method for each individual case. Trimming is accomplished either by shearing or machining. Shearing methods include punching, knife-edge die cutting, and orbital shearing. Machining methods include routing, sawing, and cutting by means of laser, water jet, or hot wire. Increasingly, the machining methods are performed by computer controlled machines or under robot control so that complicated peripheral cuts can be made accurately and uniformly at high speed. Such machines have the advantage that they can be rapidly reprogrammed to deal with other products or a sequence of products, whereas shearing methods usually require tooling dedicated to a single product.

Web-fed thermoformers using reeled or directly extruded sheet normally incorporate in-line trimming or trim-in-place tooling. The cutting method is almost always by shear punch or knife-edge means, and the machines incorporate automatic or semi-automatic waste and product handling systems. In extruder-fed machines, the waste handling system is usually arranged for full or partial recirculation to the sheet extruder.

17.4 Thermoforming molds

The thermoforming mold performs two equally important functions. It defines one surface of the product, and it acts as heat exchanger to cool the product rapidly from the forming temperature to ejection temperature. The cooling function has a direct bearing on process economics and is difficult to accomplish because all heat must be extracted through one surface of the product and because contact between the mold and the product is not as intimate as is the case for flow processes or high pressure operations.

The heat exchange function of the mold leads to a conflict of interest. Thermoforming is carried out at relatively low pressures — very low pressures in the case of vacuum forming — so molds can be constructed from light, inexpensive, easily shaped materials such as wood, plaster, or epoxy

resins. However, these materials have a poor thermal conductivity, and such molds do not function well as heat exchangers. Consequently, their use is best confined to short run or prototype use. In normal production, the improved heat transfer capability of a metal mold will more than repay the greater cost. Aluminum is most commonly used for thermoforming molds; other options include cast or sprayed low melting point alloys, porous sintered metals, and copper alloys. The molds include channels for the circulation of a cooling water. Because the forming process is performed at relatively low pressure, the channels can, depending on the material of construction and the actual working pressure, approach within about 10 mm of the forming surface for greater cooling efficiency. In the case of a cast or sprayed mold, the cooling channels can be prefabricated in copper pipe to follow closely the cavity contours. In machined molds, the channels will be drilled or milled and it is usually impossible to follow the contours so closely. The greatest cooling efficiency is achieved when the flow of water is turbulent. This is a function of the Reynolds number, and in practice it means that channels should not be too large in relation to the coolant flow rate, so running counter to the instinctive feeling that larger cooling channels must always be better.

The principal decision to be made when designing a thermoforming mold is to determine which of the two product faces is to be defined by the mold. As so many thermoformings are containers and are substantially cup or box-shaped, this decision determines whether the mold is to be of the male or female type. The shape of a thermoforming is sharply defined only on the surface in contact with the mold, so whichever is the primary presentation face of the product may determine the mold strategy. On the other hand, the forming may be produced from a sheet with a grained or textured surface and in this case, the mold may be designed to define the second surface of the product in order to preserve the sheet surface. Another consideration is to simplify the production process and machinery, and here the best choice is usually a female mold because sheet clamping is easier to arrange. Female molds also have the advantage when multiple cavities are to be placed close together. When male cores are closely spaced, there is a risk of the sheet bridging between cores and either failing to conform fully to the mold or becoming excessively thinned or even ruptured. Shrinkage also makes it

easier to release the forming from a female mold than from a male.

The cavity surfaces should be finely sand blasted to prevent formings from sticking in the mold. Vertical cavity walls require a release taper of 1° to 2°. Cores need a greater taper of at least 5°. The mold requires a multiplicity of vacuum or vent ports, and these should be distributed across the forming surface and must also be carefully sited in ribs, slots and other features that are likely to become isolated as the forming sheet progressively seals off the other ports. The ports must be small in diameter, so that little or no trace of their presence is transferred to the product as a witness mark. One rule is to make the vent diameter smaller than the thickness of the forming at that point, subject to a maximum diameter of 0.3 mm. The vents are relieved from the back of the mold by a much larger bore or a series of diminishing bores, drilled to within about 2 mm of the mold face.

The thermoforming mold may include two other important features. Pre-stretch plugs are designed specifically for a particular mold contour and should be regarded as an integral part of the mold design. There is an increasing tendency, too, for product trimming to be built into the thermoforming tooling, either by means of a peripheral knife-edge around the mold form or by providing an integral punch that separates the product by shearing it from the sheet. The advantage is that there is no possibility of sheet shrinkage producing a misalignment between the product and the trimming action. The disadvantage is that in-mold trimming increases the mechanical complication and cost of tooling, so the technique tends to be confined to high volume packaging applications.

17.5 Thermoforming with polypropylene

Polypropylenes for thermoforming typically have a melt flow index in the range 1.8 to 8.0. Homopolymers are widely used; nucleated grades are used for improved clarity and stiffness and for melt phase processing. Block copolymers are employed for improved impact strength at low temperatures, while random copolymers are selected for high transparency and improved heat sealing qualities. Stiff, high tensile modulus grades can be used to replace standard grades when wall thickness downsizing is important. Thick-walled parts are typically produced from a low MFI homopolymer grade with a high molecular weight.

Polypropylene sheet for thermoforming should be produced with a highly uniform degree of crystallinity across the web. Heating too must be uniform, both across and through the sheet. Preheating is performed at about 120°C and the final forming temperature depends on whether solid phase or melt phase processing is being undertaken. For unfilled grades of polypropylene, the solid phase forming range is typically 155°C to 165°C, with 160°C frequently quoted as the optimum. However, the true optimum depends on grade and on the required properties of the forming. Nucleated grades, for example, will normally require a slightly higher temperature than basic grades. The wall thickness, orientation, and mechanical properties of thin-walled polypropylene packaging products are substantially influenced by the sheet forming temperature, so precise temperature control is required. Temperature variations across the sheet should not be greater than 3°C.

The temperature range for melt phase forming is 170°C to 180°C; in this case the variation in

Table 17.5 Typical solid phase forming conditions for selected types of polypropylene [1124]

Polypropylene type	Forming temperature range (°C)	Optimum forming temperature (°C)	Minimum forming strain (% yield)	Maximum forming strain (% break)	Forming cycle time for 0.05in thickness (sec)
Homopolymer	160-170	160	24	3360	28
Homopolymer, 10% calcium carbonate	155-165	160	23	3280	22
Homopolymer, 30% calcium carbonate	150-165	160	21	3190	14
Copolymer	155-165	160	22	3360	26
Copolymer, 10% calcium carbonate	150-165	160	23	3180	22
Copolymer, 30% calcium carbonate	130-155	150	80	1500	30

sheet elastic response across the temperature range is relatively small and the concept of an optimum temperature has less significance.

Thermoforming molds for use with polypropylene sheet should be constructed from materials of high thermal conductivity and should be efficiently cooled. Plug assist is recommended, using low friction plugs of low thermal conductivity to avoid premature chilling of the sheet.

The shrinkage of polypropylene thermoformings is complex and is a function of sheet crystallinity and orientation as well as thermoforming conditions and orientation arising from stretching during forming. Allied to the high basic shrinkage

characteristic of polypropylene (Section 13.2.3), this makes it impossible to quote a single reliable thermoforming shrinkage figure.

References for chapter 17:

1007, 1021, 1032, 1064, 1084, 1094, 1124, 1133, 1134, 1181, 1212, 1213, 1236, 1237

18 Fabricating and Finishing

Many joining and decorating techniques are applicable to polypropylene. Joining methods such as hot gas welding, heated tool welding, adhesive bonding, and friction welding methods can all be used to join polypropylene resins to each other or to a dissimilar material. Decorating methods include painting, metallization, printing, and application of surface coverings.

18.1 Joining

18.1.1 Heated Tool Welding

In hot tool or hot plate welding, a heated platen is used to melt the joining surfaces of two thermoplastic parts. After the interfaces of the plastic parts have melted, the heated platen is removed, and the parts are held together under low pressure to form a molecular, permanent, and hermetic seal. A hot plate is used for flat joining surfaces; for curved or irregular joining surfaces, complex tools that allow the hot surfaces to match the contours of the joint interface are required.

For accurate mating and alignment, holding fixtures must support the parts to be joined. The joint surfaces should be clean and relatively smooth to the surface of the heated tool; weld quality is affected if the surfaces are contaminated by mold release agents or grease. Surfaces can be treated mechanically or chemically. [513, 495, 502]

18.1.1.1 Process

In hot plate welding, the parts to be joined are pressed against the hot platen; platens can be coated with polytetrafluoroethylene (PTFE) to inhibit melt sticking. Welding can be performed in either of two ways, referred to as welding by pressure and welding by distance. [552, 521]

In welding by pressure, the parts are brought in contact with the hot tool and a relatively high pressure is used to ensure complete matching of the part and tool surfaces. Heat is transferred from the hot tool to the parts by conduction, resulting in a temperature increase in the part over time. When the melting temperature of the plastic is reached, molten material begins to flow. Some of the molten material is squeezed out from the joint surface due to thermal expansion of the material. The melt pressure is then reduced, allowing the molten layer to thicken; the rate at which the thickness in-

creases is determined by heat conduction through the molten layer. Thickness increases with heating time — the time that the part is in contact with the hot tool (usually 1 to 6 seconds).

When a sufficient film thickness has been achieved, the part and hot tool are separated (the changeover phase) and the pressure and surface temperature drop as the tool is removed. Parts are joined under pressure, causing the molten material to flow outward laterally while cooling and solidifying. For semicrystalline polymers, recrystallization occurs at this time; recrystallization behavior is affected by cooling rates. Joint microstructure, which affects the chemical resistance and mechanical properties of the joint, develops during this time. [513, 520, 521, 495]

Welding by pressure requires equipment in which the applied pressure can be accurately controlled. A drawback of this technique is that the final part dimensions cannot be controlled directly; variations in the melt thickness and sensitivity of the melt viscosities of thermoplastics to small temperature changes can result in unacceptable variations in part dimensions. [366]

In welding by distance, also called displacement controlled welding, the process described above is modified by using rigid mechanical stops to control the welding process and the part dimensions. Parts are pressed against the hot tool under pressure, but the displacement of the parts as the molten material flows out is restricted to a predetermined distance using mechanical stops on the hot tool (melt stops) and on the holding fixture (holding or tooling stops). During melt flow, the part length decreases as molten material flows out laterally; when melt stops contact tooling stops, parts are held in place for a preset time to allow the molten film to thicken. The hot tool is removed, and mechanical stops are used again to inhibit motion of the parts, allowing the molten film to solidify only by heat conduction and not by lateral flow. Cooling time is usually 3 to 6 seconds and ends when tooling stops on supporting fixtures come into contact. Total cycle time for hot tool welding is usually 20 seconds or less. [495, 366, 511]

18.1.1.2 Processing parameters

Important processing parameters for hot tool welding are the hot tool temperature, the heating

and joining pressure, heating time, displacement allowed during heating (heating displacement), melt pressure, changeover time, welding time, and welding displacement. In welding by distance, the parameters should be set so that the displacement (also called the penetration), the decrease in part length caused by the outflow of molten material, is large enough to control part dimensions. Initially in the welding process, there is very little molten flow, and the molten film thickens. The flow rate increases with heating time, eventually reaching a steady state at which the rate of outflow equals the rate at which the material is melting; at this point in welding by pressure, the penetration increases linearly with time. When displacement stops are used, however, the penetration ceases when the melt displacement stops come into contact with the hot tool displacement stops. Until the stops come into contact, the melt will flow out laterally; afterward, the thickness of the molten material increases with time.

Molten layer thickness is an important determinant of weld strength. If the thickness of the molten layer is less than the melt stop displacement, melt stops cannot contact holding stops, part dimensions cannot be controlled, and joint quality is poor due to limited intermolecular diffusion. [514]

Melt thickness increases with heating times. For optimal molten layer thickness, heating time should be long enough to ensure that melt thickness is as large as the melt stop displacement. High heating pressures result in larger amounts of squeeze flow; displacement stops may not be reached if too much material is lost by being squeezed out of the joint, and the decreased molten layer thickness produces a brittle weld. If the molten layer thickness is greater than the melt stop displacement, molten material will be squeezed out, producing weld flash and an unfavorable molecular orientation at the interface; this reduces the quality of the joint. [512, 514, 510].

The effect of parameters on weld strength has not been investigated extensively. In experiments with polypropylene, tensile strengths approaching that of the parent material were achieved with displacements of about 2 mm. An important aspect was the heat soak time, which was influential in obtaining high joint strengths. Ideally, the stops should be as close to the joint interface as possible, consistent with bringing the joint interface into intimate contact with the heating element. After displacement stops were reached, the heating time

controlled the amount of heat soak. The optimum range found for heating time was 10–20 seconds. Without the application of displacement limit stops, the heat soaked material was squeezed out during the heating stage, thus giving joints of low strength. [518]

The hot plate temperature was found to be a less critical parameter than either heating pressure or time. Although the material displacement increased substantially with increasing temperature, the joint strength remained around 30 N/mm² for platen temperatures between 215–260°C (419–500°F). [518]

Two process parameters were involved in the weld consolidation stage: weld pressure and time. The pressure affected the material displacement, with the major portion occurring within 2 seconds of application. The weld time showed no discernible trends on either material displacement or tensile strength beyond 5 seconds. [518]

In an investigation of the butt weld strength of polypropylene plates, increased heating times resulted in increased weld strength and heating displacement. Weld strength decreased with increases in heating pressure, and both the weld strength and weld displacement decreased with increased changeover times. Weld strength decreased with increases in welding pressure and increased with increases in hold time. [510]

18.1.1.3 Polypropylene

Hot tool welding is suitable for almost any thermoplastic but is most often used for softer, semi-crystalline thermoplastics such as polypropylene and polyethylene. Dissimilar materials having different melting temperatures can be welded in hot tool welding; instead of a single platen with two exposed surfaces, two platens are used, each heated to the melting temperature of the part to be welded. Different melt and tooling displacements and different heating times for each part may be necessary, and due to different melt temperatures and viscosities, the displacement of each part will be different. Optimum processing conditions for each material must first be established, followed by optimizing process conditions for welding the two materials together. High strength welds equal to the strength of the weaker material can be achieved. [511]

Weld microstructure. The microstructure of the heat affected zone (HAZ) plays a prominent role in determining the quality of the weld. The influence of HAZ microstructure on the weld strength

was investigated by comparing micrographs of microtomed samples and tensile strength of the weld. The weld joints which had less inhomogeneity along the joining interface had better weld quality. Weld quality was very sensitive to variations in heating time; although high heating temperatures can reduce the welding cycle time, heating time should be carefully selected. [513]

In welds made from samples of polypropylene copolymer sheet, spherulites were visible within the weld, along with a visible heat affected zone of deformed spherulites separating the weld from the adjacent parent (Figure 18.1). Differential scanning calorimetry (DSC) results showed that the crystalline structure of the parent polymer was affected by the welding conditions; the main effect was the almost complete disappearance of the beta crystalline form within the weld. Impact strength of welds was 24% that of the parent material; low impact strengths may be due, in part, to the abrupt changes in visible microstructure between the weld and parent material. [488]

In experiments with welded pipes made from polypropylene block copolymer, welds with poor tensile strength were associated with a lack of a region of deformed spherulites at the weld/pipe interface, a wide weld, and a reduced amount of flow in the direction of the weld. Welds made using standard (material manufacturer recommendations) and non-standard (to study the effect of increased plate removal time; Table 18.1) conditions could be distinguished in terms of structural and morphological behavior but not always on the basis of tensile strength. Welding had little effect on the mean helical content, although increased crystallinity was evident at the centerline. Welding reduced the amount of crystalline phase orientation parallel to the pipe axis. Orientation changed to the flow direction of the weld and dropped sharply at the centerline. The amount of realignment decreased with increasing plate removal time. [515]

Transmitted light microscopy did not always

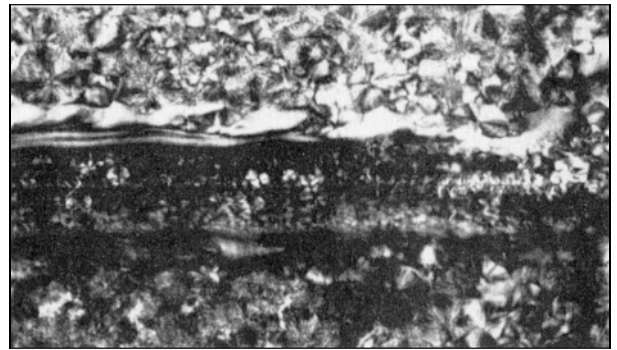


Figure 18.1 Microstructure of a hot plate weld joint (total heating time: 24 seconds, plate temperature: 250°C, welding pressure: 0.25 MPa, plate removal time: 2 seconds, cooling time: 30 seconds). Samples were cut from 6 mm thick Hoechst Hostalen sheet, an isotactic polypropylene block copolymer containing ethylene. [488]

show morphological changes that were revealed by scanning electron microscopy (SEM) examination of etched samples, such as the extent of heat affected zones, or by Fourier Transform Infrared (FTIR), such as annealed regions. The mode of etching (acid and solvent) involved the removal of disordered material between the lamellae and at the spherulitic boundaries, and it is probable that the attack was on the beta-spherulites. [515]

18.1.1.4 Non-contact hot plate welding

In direct contact hot tool welding, described above, parts are pressed against the hot tool. For high temperature polymers, the hot plate temperature required for melting is too high for non-stick surfaces to be used. In non-contact hot plate welding, parts are brought very close to the hot plate without actually coming into contact with it. Heat is transferred by thermal radiation and convection. The process is otherwise identical to hot tool welding: the hot plate is removed in the changeover phase, and pressure is applied to achieve intimate contact as the weld cools and solidifies.

Processing parameters that influence weld strength include the size of the non-contact gap, platen temperature, heating time, changeover time, and weld pressure and duration. Effects of change-

Table 18.1 Welding details and tensile results for hot plate welded isotactic pipes made from polypropylene copolymerized with ethylene

Weld	Total Heating Time (seconds)	Plate Temperature (°C)	Heating and Welding Pressure (MPa)	Plate Removal Time (s)	Tensile Strength (MPa)
Weld 1	200	205	0.1	2	20.8
Weld 2	200	205	0.1	50	20.4
Weld 3	200	205	0.1	70	10.7
Parent Material					22.0

over time and weld pressure and duration are similar to those in direct contact hot tool welding. In non-contact hot plate butt welding of polypropylene plates, using a 1 mm non-contact gap, weld strength approached or equaled bulk strength at optimal heating times which varied with hot plate temperature. Higher hot plate temperatures (480°C; 896°F) produced stronger joints at shorter heating times (40s); however, joint strength decreased at longer heating times due to excessive squeeze flow of molten material out of the joint interface and an adverse molecular orientation.

Joint strengths increased with increasing duration of weld pressure up to 60 seconds, then remained constant or decreased slightly. Optimal weld pressure was about 0.35 MPa; lower pressures allowed air entrapment in the joint, while higher pressures produced excessive squeeze flow out of the joint and an unfavorable molecular orientation during weld formation. A “push and pull” technique was applied to reduce adverse molecular orientation, consisting of applying a push force of around 200 N for one second.

18.1.1.5 Applications

Hot tool welding can be used to join parts as small as a few centimeters to parts as large as 1.5 meters (4.9 ft.) in diameter. It is commonly used in load-bearing applications and for welding large parts such as pipelines; special machines can weld large diameter pipes on site. [477, 518]

Automobile parts, such as fluid reservoirs, fuel tanks, and vent ducts, are hot tool welded. Polypropylene air ducts and mounting brackets are hot tool welded to the main part of the instrument panel, made of glass mat reinforced polypropylene, on the Mercedes-Benz S-class automobile using mechanical stops to control part dimensions. Due to a virtually 100% air, water, or dust seal, heated tool welding is widely used in joining polypropylene battery cases. [508]

Heated tool welding is used to attach a clear window to a polypropylene binder. Film with a thickness of 150–250 μm is generally used, along with a heated brass tool supported in a press. Heated tool welding is very slow for sheets above 0.5 mm thickness. For fixing a small window, hand pressure, temperatures of 150–180°C, and times of 2–5 seconds are used.

18.1.2 Hot Gas Welding

In hot gas or hot air welding, a heated gas is used to heat thermoplastic parts and a filler rod to the melting or glass transition temperature. Rod and parts then soften and fuse, forming a high strength bond upon cooling. Hot gas welding is commonly used for fabrication and repair of thermoplastic components and for lap welding of thin sheets or membranes. High bond strengths, up to 90% of the bulk material, can be achieved. [669, 671, 670, 652]

18.1.2.1 Process

Hot gas welding methods can be manual or automatic; manual methods are commonly used for short seams. In manual methods, a gas flows through a flexible tube to a hot gas gun containing a sheathed ceramic heating element. Gases used are usually nonflammable (air, nitrogen, carbon dioxide), although flammable gases (hydrogen, oxygen) can also be used; air is most common. The gas is heated to the melting temperature of the thermoplastic and is applied to the part and a thermoplastic filler rod through a nozzle or tip.

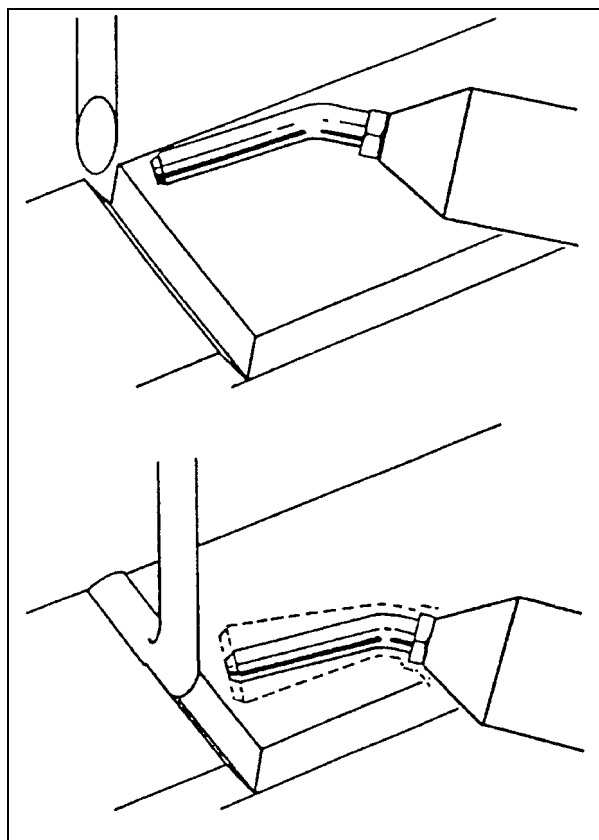


Figure 18.2 Manual hot gas welding. A heated gas flowing through the welding tip is applied to the joint interface and to the filler rod positioned at the joint. As the operator moves the tip and the filler rod along the joint, the filler rod and joint surfaces soften and fuse.

The filler rod is composed of the same material as the part and is positioned at the joint. As the operator moves the tip along the joint, the parts and filler rod soften and merge together, forming a weld after solidification (Figure 18.2). Joint surfaces should be cleaned prior to welding, using mild soap or chemical detergent and/or methyl ethyl ketone (MEK) for grease removal. [671, 652]

18.1.2.2 Processing parameters

Processing parameters in hot gas welding include welding speed, welding pressure, and hot gas temperature. Gas temperatures usually range from 200–600° C (400–1100°F), depending on the melting temperature of the plastic material; gas flow rates range from 15–600 L/min. Welding speeds vary greatly; typical speeds can range from 0.04–10 m/min (1.6–394 in./min.) or more. Because hot gas welding is frequently a manual process, parameters are adjusted continually by the operator, according to the appearance of the weld.

18.1.2.3 Polypropylene

Hot gas welding can be used to join most thermoplastics, including polypropylene. The diameter of the filler rod selected should be similar to the thickness of the part; a 0.32 cm (0.13 in.) diameter rod should be used for a part thickness of 0.32 cm (0.13 in.). For part thicknesses greater than 0.64 cm (0.25 in.), more than one rod may be necessary to reach the required thickness. [671, 507, 670]

18.1.2.4 Equipment

Equipment for manual welders consists of a welding barrel heating element, gas cylinder, pressure regulator, welding tips, welding rods, and various connectors. Automatic welders are commonly used for welding sheet material, bitumen, and roofing membranes. Air flow rates, drive speeds, and temperatures are adjustable, and temperatures and drive speeds are electronically controlled. Welding seam widths vary depending on the machine and pressure roller. With automatic welders, uniform pressure and precise tracking on uneven surfaces can be achieved, and membranes of various thicknesses can be welded.

18.1.3 Vibration welding

Vibration welding uses heat generated by friction at the interface of two materials to produce melting in the interfacial area. The molten materials flow together under pressure and bond, forming a weld

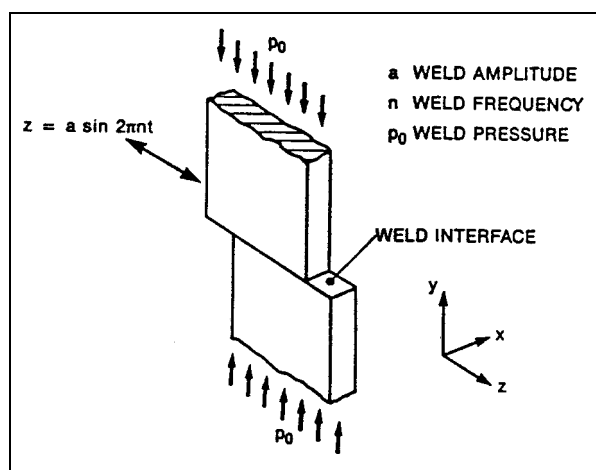


Figure 18.3 Linear Vibration Welding. Part surfaces are rubbed together in a longitudinal direction, along the z axis, generating heat through friction. Processing parameters are the weld amplitude, a , the weld frequency, n , the weld pressure, p_0 , and weld time, t . Pressure is applied along the y axis, 90° to the vibration.

upon cooling. Vibration welding can be accomplished in a short time (8–15 second cycle time) and is applicable to a variety of thermoplastic parts with planar or slightly curved surfaces. There are two types of vibration welding: linear, in which friction is generated by a linear, back-and-forth motion, and orbital, in which the upper part to be joined is vibrated using circular motion in all directions. Linear vibration welding is most commonly used, but orbital vibration welding makes the welding of irregularly shaped plastic parts possible.

In linear vibration welding, the surfaces to be joined are rubbed together in an oscillating, linear motion under pressure applied at a 90° angle to the vibration. Process parameters are the amplitude and frequency of this motion (weld amplitude and weld frequency), weld pressure, and weld time, all of which affect the strength of the resulting weld. (Figure 18.3)

18.1.3.1 Process

In the welding process, heat generated through friction raises the temperature of the interfacial area to the glass transition temperature of amorphous thermoplastics or the crystalline melting point of semi-crystalline plastics. Material at the interface begins to melt and flow in a lateral direction, and the generated heat is dissipated in the molten polymer. This viscous flow begins to increase the weld penetration, the distance the two molten materials approach each other in the interfacial area. When melting and flow reach a steady state, the vibratory motion is stopped, and the molten film solidifies under pressure.

18.1.3.2 Processing parameters

Most industrial vibration welding machines operate at weld frequencies of 120 to 240 Hz, although welding machines with higher frequencies are also available. The amplitude of the vibration, produced by exciting a tuned spring-mass system, is usually less than 5 mm (0.2 in); weld time ranges from 1 to 10 seconds (typically 1 to 3 seconds), with solidification times, after vibratory motion has ceased, usually of 0.5 to 1.0 seconds. Total cycle times typically range from 6 to 15 seconds, resulting in 4 to 10 cycles per minute. Lower weld amplitudes, (0.7 mm to 1.8 mm; 0.03 in to 0.07 in) are used with higher frequencies (240 Hz) and higher amplitudes (2 mm to 4 mm; 0.08 in to 0.16 in) are used with lower frequencies (100 Hz) to produce effective welds; low amplitudes are necessary when welding parts into recessed cavities with low clearances. [491]

Amplitude and frequency are dependent on the geometry of the parts to be joined and are set to attain a maximum frictional force. Welding at high frequencies requires less relative motion between

parts, while low frequencies require greater amplitudes. Generally, high frequencies are used when clearances between parts are restricted to less than 1.5 mm (0.06 in) and/or when flash (molten plastic that seeps out of the joint area during welding) is undesirable, as in welding brake and steering fluid reservoirs. The greater amplitudes of low frequency welding are advantageous in welding parts with long, thin, unsupported side walls oriented perpendicular to the direction of vibration. These parts are susceptible to flexing, which inhibits welding; however, the greater displacement of low frequency welding in many cases negates the effects of flexing, so that a weld can be obtained. [503, 504]

Weld pressure varies widely (0.5–20 MPa; 72–2900 psi), although usually pressures at the lower end of this range are used. Higher pressures decrease the welding time; however, higher strength of the welded parts is usually achieved at lower pressures due to a greater melt layer thickness. Weld strength is generally not very sensitive to the frequency and amplitude of vibration. [491]

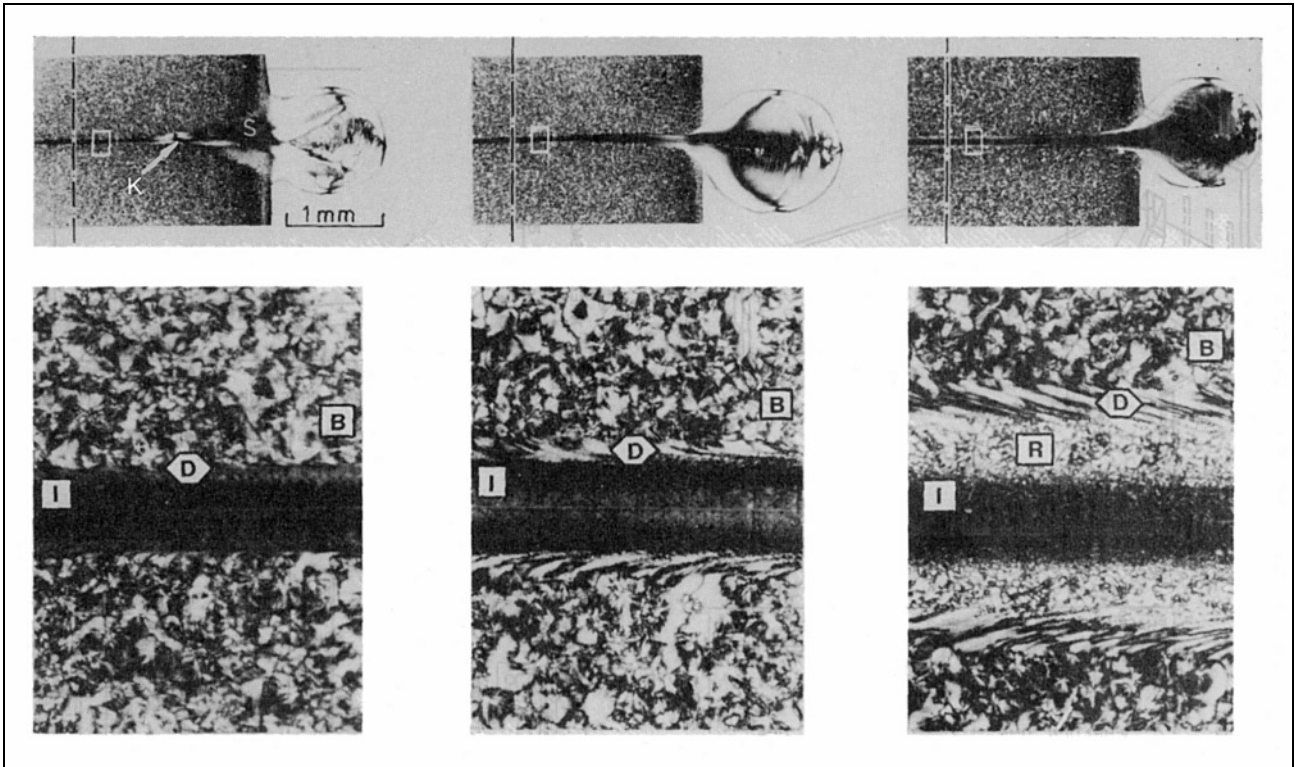


Figure 18.4 Polarization micrographs showing microstructure of three typical vibration welds of a polypropylene homopolymer. Welding pressures are a) 8.0 MPa (1160 psi) b) 2.0 MPa (290 psi) c) 0.5 MPa (72 psi). Weld amplitude is 0.7 mm (0.03 in.) In the upper micrographs, high pressure results in an area of weld thickness of about 50 μ m gradually increasing in thickness to 1 mm; high pressure causes the melt flow to change from laminar in the boxed area to turbulent at point K. At lower pressures, this area of greater weld thickness is not present. In the lower micrographs, higher pressure welds (8.0 MPa, 2.0 MPa) are separated from the bulk material (B) by two zones: an inner layer (I) adjacent to the joining plane and a layer of deformed spherulites (D). Low pressure welds (0.5 MPa) are composed of three zones: an inner layer (I), a middle zone with spherulites of different sizes (R), and a third layer of deformed spherulites (D).

18.1.3.3 Weld microstructure

Mechanical properties of the weld obtained can be correlated with weld microstructure. Although high pressures and amplitudes lead to shorter cycle times, impact strength and tensile strength decrease with increasing pressure. Figure 18.4 shows polarization micrographs of a vibration welded polypropylene homopolymer at three pressures. Low impact strength (1.1 kJ/m^2 ; $0.52 \text{ ft}\cdot\text{lb}$) at high pressure (8.0 MPa ; 1160 psi) correlated with an area of weld thickness of about $50 \mu\text{m}$ (white rectangle) gradually opening into an area with a thickness of about 1 mm (0.04 in.). This increase in thickness results from melt flow changing from laminar to turbulent at point K, producing a shear area. This shear area is not present in welds at lower pressures (2.0 MPa , 0.5 MPa) and higher impact strengths (1.8 kJ/m^2 , 3.8 kJ/m^2 , respectively). In high pressure welds (8.0 MPa ; 1160 psi), the joining plane, characterized by a bright line, is adjacent to an inner layer (I) whose microstructure cannot be determined by microscopy. It is separated from the bulk material (B) by a thin band of deformed spherulites (D). During vibration, shear is greatest in this melt/solid transition area, and the ordered spherulitic structure is disturbed by flow. Low pressure welds are wider and display three microstructural zones: an inner zone with microspherulites (I), a middle zone (recrystallized zone) with spherulites of different sizes (R), and the third layer of deformed spherulites (D). Only thick welds with three layers have high impact and tensile strength. [480, 478]

In experiments with samples cut from polypropylene-ethylene block copolymer sheets, scanning electron microscopy revealed a sharp transition between the weld and parent material; the weld itself was featureless (Figure 18.5). Differential scanning calorimetry (DSC) results showed that the crystalline structure of the parent polymer was affected by the welding conditions; the main effect was the disappearance of the beta crystalline form. Impact strength of the weld was 11% of that of the sheet material. Low impact strength may be due, in part, to abrupt changes in visible microstructure between the weld and parent material. [488]

18.1.3.4 Joint design

In designing parts for vibration welding, sufficient clearance must be provided in the joint to allow for vibratory motion between the parts, and parts must be sufficiently rigid to support the joint during

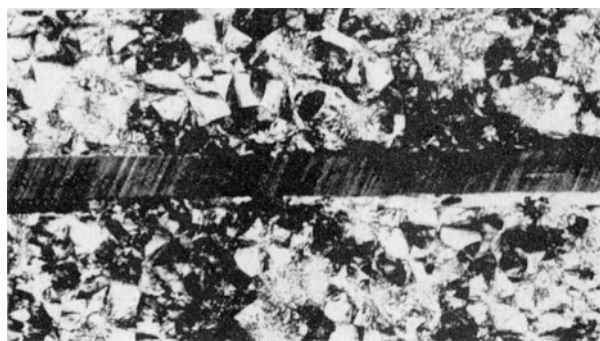


Figure 18.5 Microstructure of a vibration weld joint (frequency, 100 Hz ; weld force, 4.0 MPa ; weld time, 3 s ; hold time, 3 s ; vibration amplitude, 2.5 mm). Samples were cut from 6 mm thick Hoechst Hostalen sheet, an isotactic polypropylene copolymerized with ethylene. [488]

welding. Butt joints and tongue and groove joints are commonly used for vibration welding. Unless parts have thick walls, a flange is generally required in butt joints to provide rigidity and adequate welding surface; the flange also facilitates gripping of the parts and applying uniform pressure close to the weld. [505, 504]

18.1.3.5 Applications

Vibration welding is used extensively in the appliance industry for assembling washer and dishwasher pumps, particulate-filled soap dispensers, and dishwasher spray arms. One large electrical appliance company converted a production line of glass-filled polypropylene dishwasher pump housings from hot plate welding to vibration welding. Operation was faster, easier, more energy efficient, and easier to maintain, and better control of strength and appearance was achieved. The vibration welding process was also less labor intensive. Cycle time was 10 seconds. Design of the pump housing remained unchanged despite the shift from hot plate to vibration welding. [491, 495, 504]

Automotive applications include the welding of polypropylene compartment access doors welded in two planes. Other applications include fuel pumps, motorcycle fuel tanks, solenoid valves, and automotive emission control canisters. [491, 495, 504, 615]

18.1.4 Spin welding

Spin welding is a frictional process in which thermoplastic parts with rotationally symmetrical joining surfaces are rubbed together under pressure using unidirectional circular motion. The heat generated melts the plastic in the joining zone, forming a weld upon cooling. It is a fast, reliable

process that requires only minimal, basic equipment but that can be completely automated. It is generally used for small cylindrical or spherical components.

18.1.4.1 Process

In spin welding, one of the parts is clamped, remaining stationary throughout the cycle, while the other is spun. After the rotational speed stabilizes, pressure is applied axially, perpendicular to the joining surfaces (Figure 18.8). External, coulombic friction occurs between the two solid surfaces, generating heat. Friction results in abrasive forces which strip off surface roughness and generate wear particles. When the crystalline melting point or glass transition temperature is reached, the plastic parts begin to melt. This is an unsteady melting state in which a dramatic rise in temperature leads to a large increase in melt thickness. When melting begins, heat is generated through internal friction resulting from shear heating within the molten material. As the melt thickness increases under pressure, part of the molten material is squeezed out of the bond area into a flash bead around the interface.

A steady state friction state is then reached in which generated heat is in equilibrium with heat eliminated through bond formation along the axial direction and flash generation around the interface. In this state, the weld penetration, the distance the two molten materials approach each other, increases linearly with time, and the temperature and thickness of the molten layer remain constant. Weld formation results in an axial decrease in length of the parts being joined. Rotation is then stopped, either abruptly or by continuous ramping,

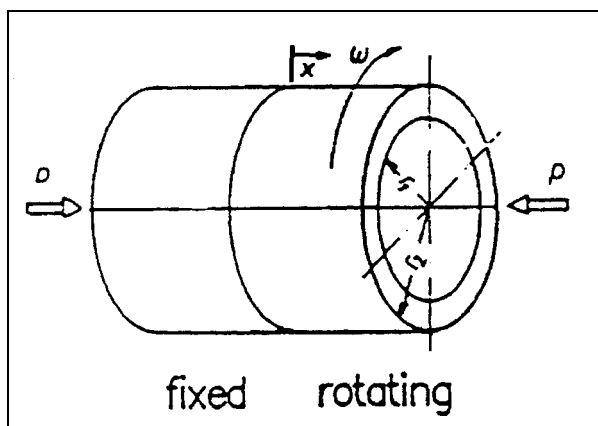


Figure 18.6 Spin Welding. One part is fixed, while the other is rotated, using unidirectional rotational motion, ω . Pressure, p , is applied axially, along the x direction. r_i and r_o are the inside and outside radii of the tubes being joined.

and the molten material is allowed to cool under pressure. Pressure is sometimes increased at this point in order to distribute the melt and squeeze out excess material. [497,496]

18.1.4.2 Processing parameters

The main process parameters for spin welding are the speed of rotation, weld or axial pressure, and weld time. Parameters used depend on the material and diameter of the joint. In commercial machines, rotational speeds can range from 200 to 14,000 revolutions per minute. Weld times can range from tenths of a second to 20 seconds; typical values are about 2.0 seconds, with an actual spin time of 0.5 seconds and a cooling time, when pressure is applied but spinning is stopped, of 0.2 to 0.5 seconds. Axial pressures range from about 1.0 to 7.0 MPa (145 to 1015 psi). Pressure must be high enough to force any contaminants or bubbles out of the joint, and the combination of speed and pressure must be controlled but high enough to cause melting at the interface as opposed to grinding. A prototype evaluation is usually done to determine optimum rotation speed, pressure, and weld time for the particular application. [78, 496, 500, 498]

18.1.4.3 Design and equipment

The main requirement for parts to be spin welded is that they, or the joint area, must be round if the part is noncircular. Also, the contacting area must be in a single plane or at least in concentric planes. Machinery varies from small, hand-operated, often homemade units, to custom made automated units integrated into an automatic assembly line.

18.1.5 Ultrasonic welding

Ultrasonic welding uses ultrasonic energy at high frequencies (20–40 kHz), that are beyond the range of human hearing, to produce low amplitude (1–25 μm , 0.001–0.025 mm, 0.000039–.00098 in.) mechanical vibrations. The vibrations generate heat at the joint interface of the parts being welded, resulting in melting of the thermoplastic materials and weld formation after cooling. Ultrasonic welding is the fastest known welding technique, with weld times of less than one second. In addition to welding, ultrasonic energy is commonly used for processes such as inserting metal into plastic parts or reforming thermoplastic parts to mechanically fasten dissimilar components.

18.1.5.1 Components of an ultrasonic welder.

Components necessary for ultrasonic welding are a generator or power supply, a converter or transducer, a booster, and a horn or sonotrode (Figure 18.7). The generator converts low voltage electricity at 50–60 Hz and 120 or 240 volts to high-frequency (20–40 kHz) and high voltage (13 kV) electrical energy. The electric current enters the converter, which contains piezoelectric ceramic crystals that expand and contract when excited by electrical energy. Electrical energy is converted into mechanical energy, and the converter expands and contracts at the frequency of the crystals. Frequencies can range from 15–70 kHz; however, the most common frequencies used in ultrasonic welding are 20 or 40 kHz. The amplitude or peak-to-peak amplitude is the distance the converter moves back and forth during mechanical vibrations. Typical values are 20 μm (0.0008 in.) for a 20 kHz converter and 9 μm (0.00035 in.) for a 40 kHz converter. [621, 618, 493]

The booster increases or decreases the amplitude of the mechanical vibrations of the converter, depending on the amplitude desired for welding,

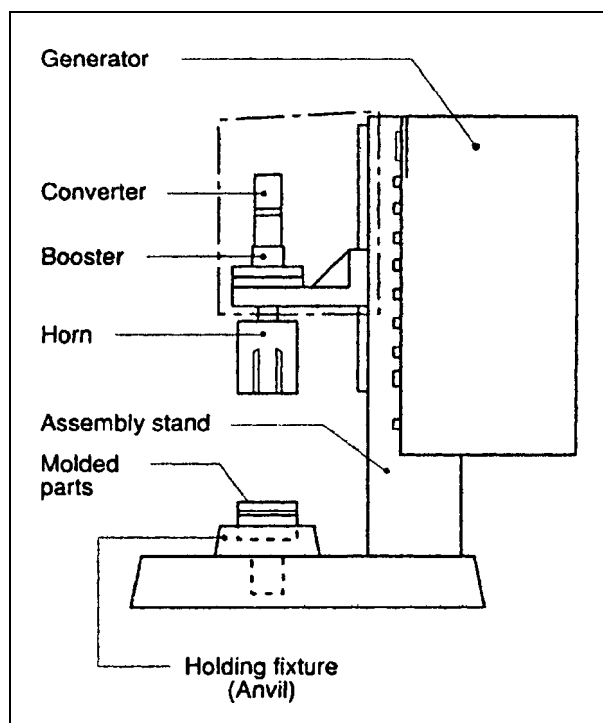


Figure 18.7 Components of an ultrasonic welder.

The generator converts low voltage electricity to high frequency electrical energy; electrical energy is converted to mechanical vibratory energy by the converter. The booster adjusts the amplitude of the vibrations and transmits them to the horn, which transmits vibratory energy to the parts. Fixtures hold parts in place and apply pressure

and conveys the vibrational energy to the horn or sonotrode. The horn, made of titanium or aluminum, can further increase the amplitude of the mechanical vibrations. It contacts one of the parts during welding and transmits vibratory energy to the part. For optimal energy transmission, the end of the horn that contacts the part is designed to mate with the part geometry. Fixtures hold the parts in place and apply pressure during welding. An assembly stand is present in some welders, in order to prevent movement or flexing of the welding stack during welding. Ultrasonic welding begins after parts have been loaded and a particular force (trigger force) or distance has been reached by the horn. [621, 618, 493]

18.1.5.2 Process

Ultrasonic vibrations applied to the part under pressure generate sinusoidal standing waves throughout the parts being welded at frequencies of usually 20 kHz or 40 kHz. In a viscoelastic material such as a thermoplastic, this energy produced under sinusoidal strain is dissipated through intermolecular friction, resulting in a buildup of heat. The oscillating wave pattern produces nodes with zero displacements, as well as regions in the parts that are subjected to high amplitude motion. Optimal transmission of ultrasonic energy to the joint, and subsequent melting behavior, is dependent on geometry of the part. Part motion is complex and not completely understood. However, results have indicated that for parts without energy directors, maximum strain and heating occurs at displacement nodes; for parts with energy directors, maximum heating occurs at displacement antinodes. Heat is generated by friction of the part surfaces and by energy dissipation through intermolecular friction. Heat generated is highest at the joint surface due to surface asperities, which are subjected to greater strain and frictional force than the bulk material. [477, 546, 543]

In many part geometries, an energy director is molded into the part. An energy director is a triangular-shaped protrusion located at the joint interface (a man-made surface asperity) that is used to concentrate ultrasonic energy at the part surface (Figure 18.8). An energy director concentrates stress at its point in the joint interface. During welding, horn vibration is perpendicular to the joint surface, and the point of the energy director is forced into contact with one of the parts being welded. Heat generation is greatest at this point,

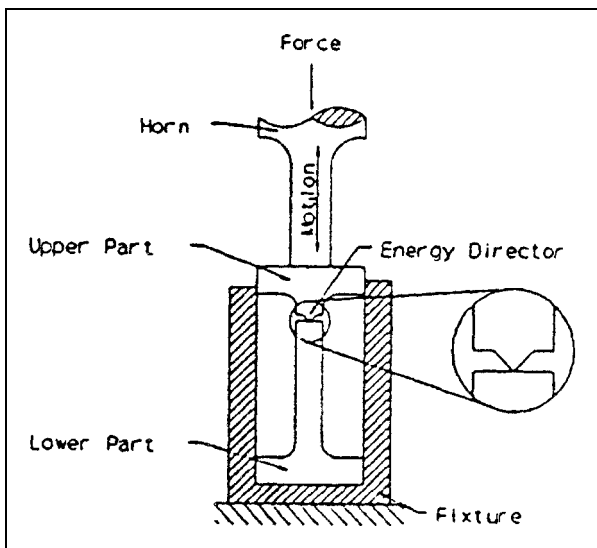


Figure 18.8 Ultrasonic welding using an energy director. The energy director is molded onto the upper part being joined. During welding, the horn is in contact with the upper part, and force is applied perpendicular to the axis of the weld interface. Vertical vibratory motion applied to the part results in heat generation and melting of the energy director.

and the energy director melts and flows into the joint. The displacement, the decrease in distance between the parts that occurs as a result of melt flow, increases rapidly, then more slowly as the molten energy director spreads out and contacts the cooler part surface, and the melting rate drops. The part surfaces meet, and the melting rate increases. Steady-state melting then occurs; a constant melt layer thickness forms in the weld, accompanied by a constant temperature distribution. When maximum displacement is reached, additional melt is squeezed out of the joint interface. Intermolecular diffusion during melt flow results in new polymer chain entanglements between the two parts being welded, which produce a high strength weld. [537, 477, 546]

After a specific time has elapsed, or after a particular energy, power level, or distance has been reached, the converter is turned off, and ultrasonic vibrations cease. [477, 537, 546]

18.1.5.3 Near field and far field ultrasonic welding

Two types of ultrasonic welding are possible, near field and far field. In near field welding, the contact surface of the horn is 0.6 mm (0.25 in.) or less away from the joint surface. In near field welding, the horn should fit the contour of the part it contacts. In far field welding, the distance between the horn and the joint surface is greater than 0.6 mm

(0.25 in.). Because ultrasonic energy is transmitted through the upper part being welded, far field welding is dependent on the ability of the material to conduct vibratory motion and can be used for rigid plastics. Generally, energy transmission is more efficient as the distance between the horn and the part surface decreases. With near field welds, the amplitude of vibration at the joint surface is 95% of that at the horn surface. Far field welding requires higher amplitudes, longer weld times, and higher air pressures to achieve weld quality comparable to that of a near field weld and is generally recommended only for amorphous polymers. [493, 618, 543, 631]

18.1.5.4 Processing parameters

Important processing parameters in ultrasonic welding are weld time, (the time vibrations are applied), weld pressure or force, hold time (the time allowed for cooling and solidification after vibration has ceased), hold force, trigger force (the force applied to the part before ultrasonic vibrations are initiated), power level, and amplitude of vibration. The horn must be properly positioned in contact with the top part before ultrasonic vibrations are initiated; welding cannot be performed successfully if the horn contacts the part after vibrations have begun. Vibration frequency is usually 20 or 40 kHz; frequency depends on the ultrasonic welder used. In production, high amplitudes and short weld times are commonly used.

In studies with polypropylene, near field ultrasonic welding was successful, but amorphous materials (ABS, impact polystyrene) produced stronger bonds. It was generally found that increasing the weld pressure initially increases the weld strength, with further increases in pressure decreasing strength due to unfavorable molecular alignment. Increasing the weld time increased energy dissipated and strength; the strength leveled off at weld times greater than 1.5 seconds. Increasing the amplitude of vibration increased the energy dissipated and strength more than with amorphous polymers such as ABS and polystyrene — with the exception of low amplitudes. [543, 544, 540]

18.1.5.5 Polypropylene

Semicrystalline plastics such as polypropylene are characterized by regions of ordered molecular structure. High heat is required to disrupt this ordered arrangement. The melting point is sharp, and re-solidification occurs rapidly as soon as the tem-

perature drops slightly. Melt that flows out of the heated region of the joint solidifies rapidly. When in the solid state, semicrystalline molecules are springlike and absorb a large part of the ultrasonic vibrations instead of transmitting them to the joint interface, so a high amplitude is necessary to generate sufficient heat for welding. [620, 618]

Near field welding with shear joints generally produces better welds with crystalline materials. Polypropylene does not weld as easily as rigid, hard polymers, such as polystyrene, but good results can be achieved if a high amplitude, high energy source is used. Only near field welding is possible, however, since polypropylene does not transmit ultrasonic waves well enough to allow far field welding.

In experiments, far field welding with energy directors was not possible. The parts melted during welding at the interface between the horn and the parts, and the energy directors melted only a little or not at all. It was suggested that better results could be obtained with a different part geometry that places the joint interface at a displacement antinode. This is done by designing the top part to be a half a wavelength. [543, 454, 541]

Consistent welds were obtained when welding the periphery of non-woven polypropylene filters, in order to block out contaminants, using amplitude reduction during the welding cycle. In amplitude reduction, an initial high amplitude is reduced during the welding cycle. Most olefin fibers, both woven and non-woven, have good ultrasonic welding characteristics. The problem in this application was consistency because of inconsistent density in the nonwoven fabric. This density variation is magnified when the part is welded, due to the sharp transition of the material as it melts. The power draw remains fairly constant for most of the process yet rises dramatically at the end of the weld when the material melts. If the weld time extends beyond this point, over welding occurs. If the weld is discontinued prior to this point, no fusion occurs. Thus, a proper weld time has a very narrow range. When the amplitude was reduced at a pre-set power level, the slope of the power curve was reduced. This resulted in slowing the process and controlling the melt of the material which created a more robust process and consistent/uniform welds. [532]

Different grades of the same material may have different flow rates; one part may melt and flow but not the other, and no bond will form. [620, 493]

In order to achieve maximum ultrasonic weld joint strength in polypropylene, processors should consider the following:

- Welding input parameters optimization needs to be linked directly to part acceptance, whether it be pull or burst strength, hermetic seal integrity, or other factors.
- Reliance on travel distance, weld energy, or time should not be made in order to assume maximum joint strength while trying to optimize the process.
- Maximum joint strength can be obtained by welding at a primary weld force and then switching to a lower weld force.
- Changing amplitude during the welding cycle either upwards or downward does not have a positive impact on weld strength.
- Precise, closed-loop control over the weld force is critical to weld strength, since minor force changes greatly influence weld strength.

18.1.5.6 Dissimilar materials

In welding dissimilar materials, the melt temperature difference between the two materials should not exceed 22°C, and both materials should be similar in molecular structure. For large melt temperature differences, the lower melting material melts and flows, preventing enough heat generation to melt the higher melting material. Only chemically compatible materials that contain similar molecular groups should be welded; higher bond strength is obtained with greater percentages of similar molecular groups. Compatibility exists only among amorphous plastics or blends containing amorphous plastics. Semicrystalline polypropylene and polyethylene have many common physical properties but are not chemically compatible and cannot be welded ultrasonically. [620, 501, 631]

18.1.5.7 Joint design

Joint design is crucial for optimum results in ultrasonic welding. Joint design depends on the type of thermoplastic being bonded, part geometry, and requirements of the weld. Designs for ultrasonic welding should have a small initial contact area between the parts to be welded to concentrate the ultrasonic energy and decrease the total time needed for melting. Mating parts should be aligned and should be in intimate contact but able to vibrate freely in relation to each other in order to create the required friction for welding. Mating surfaces should be uniform, and the surface in

contact with the horn should be large enough to prevent its sinking into the plastic during vibration. [551, 505, 618, 631]

Various joint designs are used with energy directors. The butt joint is one of the simplest and most common designs. Because butt joints do not self-align, fixtures are necessary for part alignment. Hermetic seals with butt joints are difficult to achieve with semicrystalline polymers. The melt is exposed to air during welding, which can accelerate crystallization and cause oxidative degradation of the melt, resulting in brittle welds. [621, 631, 505, 618, 551]

The step joint (Figure 18.9) and tongue and groove joint, both with energy directors, eliminate flash on the exterior of the joint and are useful when cosmetic appearance is important. In the tongue and groove joint, the melt is completely enclosed in a groove in the joint, which is slightly greater than the tongue. It is used to prevent flash when cosmetic appearance is important and aligns the parts so that additional fixtures are not necessary. [631, 505, 618, 551, 621]

Energy director joints can be easily fabricated, and tolerances are not critical. They can be used for rectangular shapes and for thin sections where other joint designs are not feasible. Disadvantages of energy directors are that the part containing the energy director should contact the horn, hermetic seals are not reproducible, and lower strength welds are obtained. [581]

The shear joint is used in welding semicrystalline materials that have a sharp and narrow melting point. Energy directors are not as useful

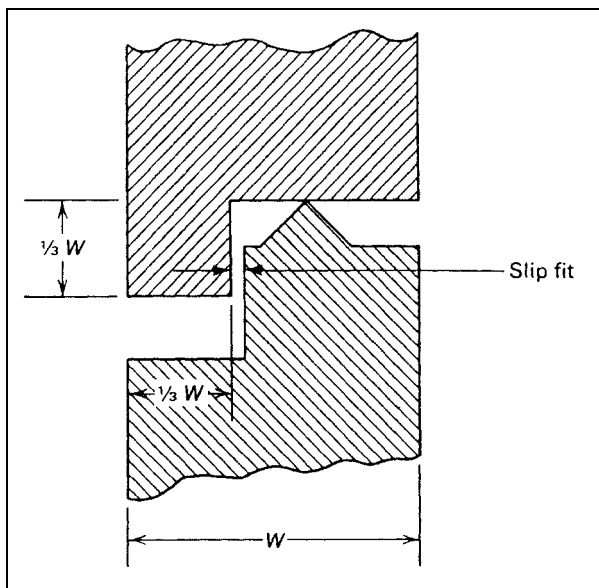


Figure 18.9 A step joint with energy director.

with crystalline materials because material displaced from the energy director either degrades or recrystallizes before it can flow across the joint interface and form a weld. [631, 505, 618, 551]

Higher energy is necessary when using shear joints with semicrystalline materials, due to the greater melt area and the high energy required for melting crystalline materials. This requires either longer weld times (up to 3-4 times longer than other joints) or greater power (3000 W instead of 2000 W) and greater amplitudes. [505, 618, 551, 581]

18.1.6 Induction welding

Induction welding uses induction heating from high radiofrequency alternating current to magnetically excite ferromagnetic particles embedded in a thermoplastic or adhesive matrix at the joint interface of the two parts being welded. The heat released is used to melt and fuse thermoplastics and heat hot-melt adhesives. It is a reliable and rapid technique, ranging from fractions of a second for small parts to 30–60 seconds for parts with long (30 cm; 157 in.) weld areas, and results in structural, hermetic, or high-pressure welds. [582, 454, 583]

Induction welding is a type of electromagnetic welding which uses electromagnetic energy at frequencies of 0.1 kHz — 10 Mhz to heat materials. Induction welding is frequently referred to as electromagnetic welding. [575]

18.1.6.1 Process

Heat is generated in induction welding from interaction of the magnetic field with the ferromagnetic material and from current induced in the metal. The high frequency alternating current moves through a copper coil, generating a rapidly reversing magnetic field. Ferromagnetic materials align with the magnetic field; alignment changes as magnetic field direction changes. Atoms do not return to the initial alignment existing before the magnetic field changed direction but to a slightly different alignment, resulting in heat losses within the metal which are transferred to the plastic matrix through conduction. Additional heat generation results from voltage within metallic ferromagnetic material induced by alternating current. [590]

High frequencies are achieved using an induction generator, which converts a 50–60 Hz power supply to frequencies of usually 1.8–10 MHz and output power of 1–5 kW. The magnetic field is formed by passing high frequency current through work or induction coils, water-cooled copper coils

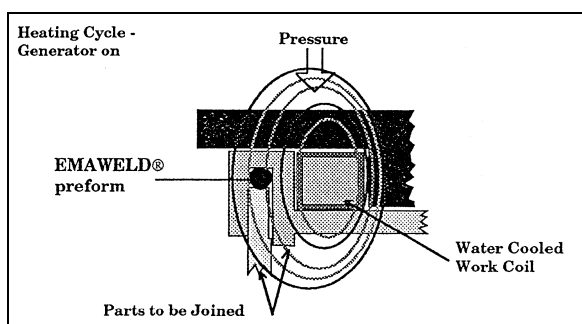


Figure 18.10 The induction welding process. Parts being joined are placed near work or induction coils, and pressure is applied. An induction generator supplies radiofrequency alternating current to the coils, generating a magnetic field. The ferromagnetic material heats up, melting the surrounding thermoplastic matrix, which then flows along the bond line. EMAWELD preform includes the ferromagnetic material and the thermoplastic matrix.

of different sizes and shapes. Electromagnetic fields become exponentially more concentrated as the distance to the coil decreases, so that joints placed as close as possible to the coil maximize heat transferred to the electromagnetic material.

In the induction welding of thermoplastics, electromagnetic (EMA) materials not molded into the part are placed in the joint before welding (Figure 18.10). Slight pressure (0.1–0.3 MPa; 14–44 psi) is applied to the parts to be welded, and high frequency current is passed through the coil. Heat generated in the EMA material results in a rapid temperature rise. Heat is conductively transferred to the thermoplastic matrix surrounding the ferromagnetic particles, and the molten thermoplastic matrix of EMA material flows along and fills the joint line, flowing into any voids or surface irregularities and forming a weld as it cools. Bond strength is proportional to the surface area of contact; however, it is important that the molten flow be contained within the joint area by internal pressure directed against the weld surface. [582, 583, 501]

18.1.6.2 Processing parameters

The most important determinants of bond quality in induction welding are the joint design and work coil design. Proper coil and joint designs are essential for good welds and determine whether or not electromagnetic welding can be used successfully.

Other parameters that influence the induction welding process include power output of the generator, frequency applied to the work coil, and type and design of the electromagnetic filler material. Higher power output is necessary for larger parts or parts with greater joint length. To maintain a particular strength of the magnetic field around the

EMA filler material, power output and frequency must increase as the coupling distance between the joint and the coil increases. Cycle time for the induction welding process is dependent on the type and particle size of electromagnetic filler, cross-sectional area of the electromagnetic filler enclosed in the thermoplastic matrix, power output, frequency, and part size. These parameters are tailored for each specific application. [583, 477]

18.1.6.3 Electromagnetic filler material

The electromagnetic filler material is composed of micron-sized particles of metallic (iron, stainless steel) or nonmetallic, ceramic (ferrite) material. The frequency used for welding depends on the composition of the EMA filler material. For bonding thermoplastics, the filler material is enclosed in a thermoplastic matrix that is compatible with the plastics being joined. [583, 501, 582, 583]

Type and cross-section of the EMA material (ferromagnetic filler + thermoplastic matrix) are dependent on the size and shape of the parts to be welded and on the position of the work coils. EMA material is supplied in many different forms: strands and extruded profiles (continuous reels and precut), tapes and strips up to 30 cm (11.8) wide, and stampings and injection-molded parts. Shape and formulation must be carefully considered for each application, and maximum efficiency may require production of a custom-made material. [582, 477]

18.1.6.4 Materials

Induction welding is less dependent than other welding methods on the properties of the materials being welded. It can be used to weld almost all thermoplastics, crystalline and amorphous, and can weld hard-to-weld polyolefins. In welding filled materials, the amount of thermoplastic resin in the EMA material can be increased to compensate for the filler content in the parts. A greater volume of melt will be produced during welding, resulting in a higher-strength bond. Reinforced plastics with filler levels up to 65% have been successfully welded. [506, 367, 501]

18.1.6.5 Applications

In the automobile industry, EMA filler with a polypropylene matrix was used to produce station wagon structural load floors composed of a GMT 40% glass mat composite. The GMT composite replaced stamped steel, resulting in decreased weight and less noise under vibration testing. Continuous

welding of two halves was used, with EMA material placed at the interface of the flat panel and the ribbed shell (Figure 18.11). During welding, polypropylene from the EMA matrix was added to the weld interface, increasing the strength of the high-glass content weld. A uniform structural weld was produced in 15 seconds, with consistent weld strength over 1000 psi (6.9 MPa) on a one inch square overlap. Load floors withstood a static load of 50 lb./ft.² at 82.2°C with less than one inch deflection and a 15° torque test without bond failure. [583]

The use of EMA compound at the interface of the flat panel and the ribbed shell was critical in attaining the necessary structural weld. Since polypropylene was added to the weld interface, the difficulties associated with the high glass content of the GMT were overcome. The EMA material actually bonds to the glass and welds to the surrounding polypropylene matrix. As the EMA material melts and flows under pressure, the surface irregularities are filled. The resultant weld provides a uniform structural weld between the two mating parts.

In the appliance industry, a two-piece polypropylene teakettle was welded together using induction welding. Although polypropylene is one of the most difficult thermoplastics to weld using other methods, it is one of the easiest materials to bond using electromagnetic welding. Induction welding was chosen over hot tool welding due to aesthetics and improved part fit. A completely contained joint and induction welding fixturing that provides exact part alignment 100% of the time was used to achieve these results. A leak proof (almost 100% reliability) seal and high reliability (100%) was obtained. Cycle time was 11 seconds. [506]

18.1.7 Radio Frequency Welding

Radio-frequency (RF) welding, also called high frequency welding or sealing, heat sealing, and dielectric welding or sealing, uses high frequency (13 to 100 MHz) electromagnetic energy to generate heat in polar materials, resulting in melting and weld formation after cooling. A high intensity radio signal is used to impart increased molecular motion in two similar or dissimilar polymers. This causes a temperature rise, resulting in melting and increased polymer chain mobility. Ultimately, the polymer chains of the two materials penetrate their interface and become entangled, forming a weld. [575]

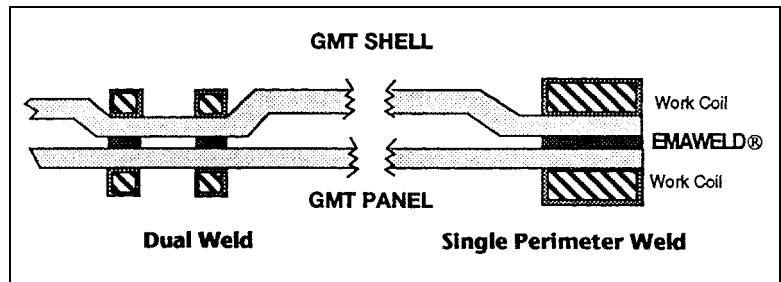


Figure 18.11 Panels composed of a GMT 40% glass mat composite used to produce station wagon structural load floors. Panels were welded using induction welding. Two coil designs are possible, depending on structural requirements of the weld: a single weld located at the end of the part, or a dual weld, placed at the interfaces of the flat panel and ribbed shell.

18.1.7.1 Polypropylene

Polypropylene is difficult to join with this method, except for special film grades. Generally, materials being joined must have polar groups in their molecular structure, unless a conductive polyaniline (PAN) composite is placed in the joint interface for heat generation. [571]

18.1.8 Microwave welding

Microwave welding uses high frequency electromagnetic radiation to heat a susceptor material located at the joint interface; the generated heat melts thermoplastic materials at the joint interface, producing a weld upon cooling. Microwave welding is a type of electromagnetic welding and uses frequencies of 2 to 10 GHz. [575]

18.1.8.1 Process

Heat generation occurs in microwave welding through absorption of microwave energy by susceptor materials that contain polar groups as part of their molecular structure or that are electrically conductive. In an applied electric field, polar groups align in the field direction. In a microwave, the magnitude and direction of the electric field changes rapidly; polar molecules develop strong oscillations as they continually align with the field, generating heat through friction. [599]

18.1.8.2 Susceptor material

Polyaniline (PAN) doped with an aqueous acid such as HCl is used as a susceptor in microwave welding. Doping with dilute aqueous acid introduces polar groups into the molecular structure and makes the material electrically conductive by providing free moving electrons. The amount of heat produced during welding is dependent on the

conductivity. If the material is not conductive enough, mobility of free charges is low and very little heating occurs. If conductivity is too high, microwave energy is reflected, not absorbed, so that no heating occurs. PAN is an “A-B” type polymer with a conductivity ranging from that of an insulator to 400 S/cm, depending on the doping material used.

For welding thermoplastics, acid-doped PAN powder and a thermoplastic material is compression molded into a gasket that is placed at the joint interface. Bulk material in the parts being joined is not affected by microwave heating unless the molecular structure includes polar groups. [575, 599]

18.1.8.3 Processing parameters

Important processing parameters in microwave welding are the heating time, power level, welding pressure, and percentage of conductive polymer in the gasket. These parameters affect the amount of heat generated and the weld strength. Higher power levels result in higher temperatures, faster heating rates, and dramatically decreased welding times. Heating time should be carefully controlled in microwave welding; at high power levels, temperatures at the joint interface can exceed 200°C (392°F) in less than five seconds. The heating rate changes with temperature and decreases at higher temperatures due to loss of PAN conductivity and consequent irreversible loss in absorption. Absorption of microwave energy is also influenced by gasket orientation. The conductive gasket responds to the directional electric field generated in the microwave system. [598, 575]

18.1.8.4 Applications

Microwave welding is a new process currently being developed. It may be useful in polypropylene — it does not contain polar groups in its molecular structure and will not be susceptible to overheating.

18.1.9 Resistance welding

In resistance welding, also called resistance implant welding, current is applied to a conductive heating element or implant placed at the joint interface of the parts being welded. The implant is heated through Joule heating, and the surrounding plastic melts and flows together, forming a weld. Joint strengths of thermoplastics are higher with this welding method than those obtained with adhesive bonding. [558]

18.1.9.1 Process

Heating elements can be carbon fiber prepegs, woven graphite fabric, or stainless steel foil or mesh. Stainless steel heating elements can be used alone in welding thermoplastics; for welding thermosets or metals, they are impregnated with a thermoplastic or sandwiched between two thermoplastic layers, such as glass / polyetheretherketone (PEEK) coated with thin layers of PEEK film. Carbon fiber prepegs are reinforced plastics usually composed of unidirectional carbon fibers in a thermoplastic matrix. Stainless steel heating elements introduce foreign material into the joint but are used to minimize any potential for galvanic corrosion and to reduce fiber motion, which has a detrimental effect on joint strength. The heating element comprises the innermost portion of the weld stack (Figure 18.12) used in resistance welding. The heating element is sandwiched between the parts to be joined, referred to as the ad-

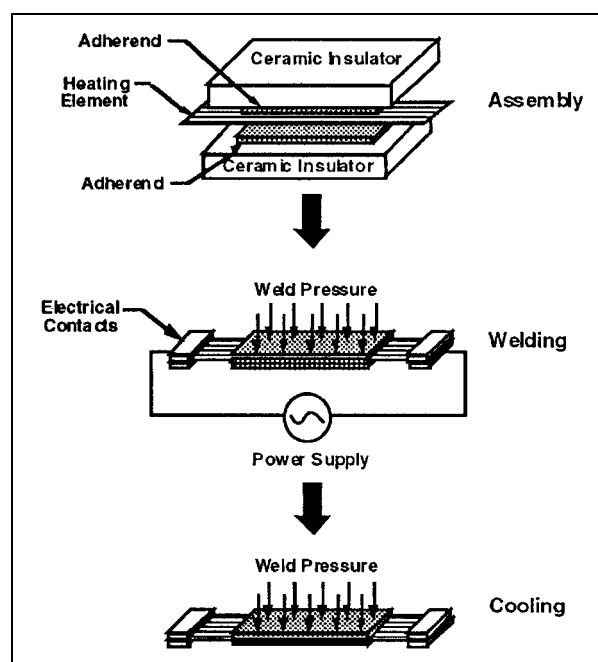


Figure 18.12 The resistance welding process.

- **Assembly:** A weld stack is assembled, consisting of a heating element sandwiched between two adherends; thermoplastic interlayers may also be present between the adherends and heating element. An insulator is placed on the outermost ends of the stack.
- **Welding:** To begin welding, electrical contacts are connected to a power supply, and pressure is applied to the insulator. Heat is transferred from the heating element to the thermoplastic material in the weld stack, and the thermoplastic melts and flows.
- **Cooling:** Pressure is maintained as the current is shut off, allowing cooling of the molten plastic and weld formation.

herends. Insulators on the outermost ends of the weld stack complete the assembly. The weld stack can be autoclaved for consolidation. [558, 563, 566, 559, 564, 562, 559]

To begin the welding cycle, pressure is applied to the weld stack, and electric current is passed through the heating element. Joule heating of the implant causes a rise in temperature; the adjoining thermoplastic material melts and flows under pressure. Any surface irregularities are smoothed out, and molten plastic is squeezed out of the weld interface, removing any interlaminar voids. Intimate contact between the two thermoplastic materials is achieved as thermoplastic molecular interdiffusion (healing) and polymer chain entanglements occur. The power is turned off, allowing cooling and solidification of the weld under pressure.

18.1.9.2 Processing parameters

Processing parameters include power or current applied to the heating element, weld pressure, peak temperature, and dwell time, time held at the peak temperature or current. Optimal parameters have not been established. [563, 559, 566]

18.1.9.3 Polypropylene

In resistance welding experiments using short fiber, glass reinforced polypropylene (GRPP), low power (50 kW/m^2) and weld pressure (0.062 MPa; 9 psi) were used to minimize squeeze flow out of the joint and part deformation of the short fiber thermoplastic composite. Dwell times ranged from 0–60 seconds, at peak temperatures (measured using an embedded thermocouple) of 175°C or 195°C . A stainless steel screen was used as a heating element. Uniform, high strength welds were obtained under all welding conditions studied, except with the lower temperature and 0 second dwell time. Screens were cleaned before welding in acetone and an alkaline solution. Shear strength ranged from 16.6–18.1 MPa (2407–2624 psi) Examination of bond surfaces after fracture showed that the heating element was not incorporated into the bond; bond formation occurred through GRPP percolation through the heating element and not from adhesion between the heating element and the GRPP composite. [563]

The low thermal conductivity of short fiber composites, such as GRPP, allows heat to be focused at the joint interface during welding. Thermocouple temperature measurements during welding of GRPP (at 50 kW/m^2 , 0.062 MPa,

195°C) indicated that high temperatures were present only at the joint surface; ambient temperatures were recorded farther from the weld. Deformation and distortion of short fiber or mineral filled composites may occur during resistance welding due to the pressure applied to the parts. In welding GRPP, temperatures 10–15% above the melt temperature, low power (50 W/m^2) and pressure (0.062 MPa), and short dwell times (30 s) produced uniform welds with good shear strengths (17.0 MPa) in a process time of 2 minutes. [563]

18.1.10 Extrusion Welding

Extrusion welding is a reliable technique developed from hot gas welding, in which a thermoplastic filler identical to the material being welded is extruded into a groove in the preheated weld area. The filler material fills the groove and forms a weld after cooling. Extrusion welding is usually performed manually, although it can be automated.

18.1.10.1 Process

In the extrusion welding process, cleaned, ground, and scraped parts are positioned in a specified geometry, and the welding area is preheated by hot air from a nozzle that moves along the joint line just before the welding shoe. Both the hot air nozzle and the welding shoe are attached to a weld head, which moves along the joint line at a particular welding velocity. Molten extruded thermoplastic material is applied under pressure by the welding shoe and flows out of the welding shoe, filling the joint area. The process is similar for a lap seam used in joining waterproofing membranes, except that joining pressure is applied to the flat membranes during welding. [561, 617]

18.1.10.2 Processing parameters

Welding parameters important in determining the quality of the weld include the hot air temperature, hot air flow velocity and volume, welding velocity, geometry of the weld shoe, and temperature, flow rate, and pressure of the extruded material. Weld velocity is dependent on the flow velocity of the extrudate, which is constant during welding, the weld geometry, and the thickness of the parts being welded. The flow rate of extruded material is controlled by revolutions of the barrel extruder and is adjusted to match the welding velocity and the geometry of the weld. Maximum pressure of the extrudate depends on the extrudate temperature and on the width of the root gap, the gap between

the parts being joined. Since extrusion welders are usually manually operated, the effects of parameters on weld quality have not been extensively investigated. [569, 617]

Preheating of the joining surfaces, in order to form a surface melt layer, is essential for obtaining a good quality weld and is the most important determinant of the mechanical properties of the weld. Parameters that influence the preheating process include hot air temperature, welding velocity, geometry of the air nozzle, and thickness of the parts being welded. Greater melt thicknesses produce welds of greater strength; with polypropylene welds, high strength in tensile creep tests was obtained at a weld thickness of 0.25 mm (0.0098 in.). Melt thickness increases with increasing hot air temperature and decreases with increases in welding velocity. A minimum melt layer of thickness of 0.8 mm (0.03 in.) is necessary for formation of a multilayer microstructure in polypropylene welds that is correlated with high weld strength in bending tests. With optimum parameters (4.5 mm/s or 0.18 in./s welding velocity, 360°C hot air temperature, 200 L/min. volume flow), a welding factor of 0.7 was achieved; welding factor is a ratio of weld strength over bulk strength. [569, 617]

18.1.10.3 Weld microstructure

The microstructure of a polypropylene weld with high weld strength in bending tests consists of five layers. Bulk material that is unaffected by the welding process is at the outer region of the weld zone. The next layer consists of deformed spherulites that did not completely melt during preheating and welding. Recrystallized bulk material in the next layer is the innermost layer of bulk material and is thinner than the molten melt produced during preheating. A transcrystalline layer separates bulk from extruded material. Spherulites in this layer show a preferential growth direction and a crystal modification (β - modification) that often occurs in shear zones. Extruded or filler material is found in the innermost layer. In bending tests, cracks begin adjacent to the filler layer and propagate through the recrystallized layer and the bulk material. [617]

18.1.10.4 Applications

Extrusion welding is a cost effective process that can be used to weld parts of varying geometries, and thick polyolefin parts can be welded in one step. It is commonly used in apparatus engineering

and in laying waterproofing membranes for ground water protection applications, using extruded sheet and profiles made of polyolefins. [564, 569, 617]

18.1.11 Infrared Welding

In infrared welding, the joining surfaces of thermoplastic parts are heated to the melting temperature using infrared radiation, at wavelengths ranging from 1 to 15 μm . When melting begins, parts are brought together under pressure, forming a weld upon cooling. Infrared welding is a non-contact welding method; part surfaces are not in direct contact with the heat source but are at distances of up to about 20 millimeters. The high temperatures that can be obtained at short heating times makes this method especially suitable for temperature resistant materials.

18.1.11.1 Process

Infrared welding is similar to hot tool welding. Joint surfaces of the parts to be welded are held at a specified distance from the heat source, a radiant heater or lamp, and are heated to the melt temperature of the plastic. When a molten layer of a desired thickness is obtained, the radiant source is removed, and the parts are brought together under pressure. The elapsed time from removal of the heat source to contact of the parts is the changeover phase. Pressure is applied to achieve intimate contact between the parts, and molecular diffusion across the joint interface determines joint strength. Pressure is applied until the joint cools and solidifies. [525, 523]

18.1.11.2 Processing parameters

Major processing parameters in infrared welding are the heating time, distance between the parts being welded and the radiant heat source (heating distance), time required for the changeover phase, and the welding pressure after removal of the heat source. Heating temperature depends on the melt temperature of the plastic and the geometry of the welding assembly (part dimensions, heating distances). In diffusion radiators without reflectors, radiation intensity decreases as heating distance increases. Decreased radiation intensity results in slower temperature increases and smaller temperature gradients in the weld zone and reduced thermal stress; however, longer heating times are necessary to achieve a particular melt thickness. [526, 524, 525, 523, 538]

Thickness and properties of the melt layer are an important determinant of joint strength. Melt thickness is dependent on the amount of radiation reaching the weld interface and is influenced by heating time, heating temperature, heat source, geometry of the welding assembly, and characteristics of the polymers being welded. [526, 523]

In studies with polypropylene, increasing the heating time increased the thickness of the molten layer, resulting in slightly increased joint strength until an optimum time was reached; further increases decreased strength due to polymer decomposition both on and below the joint surface. Increasing the heating distance required substantial increases in heating time to achieve the same joint strength, resulting in longer cycle times. During the changeover phase, cooling of the molten polymer occurs, so that increased changeover times reduce molten layer thickness and joint strength. Increased welding pressure generally increases weld strength due to squeezing out of decomposed material, until an optimum is reached. Further pressure increases result in decreased molten layer thickness, and weld strength decreases. The molten layer produced at short heating times may not be thick enough for good joint strength, so that any increased pressure squeezes out some of the molten layer, further reducing joint strength. [525]

Joint strengths equal to bulk strength (33 MPa) were obtained with optimal processing parameters:

heating time of 11 seconds, changeover time of 0.8 seconds, and hold time of 11 seconds. Cycle time was 23 seconds. In contrast, hot plate welding produced joint strengths of only 85% of bulk strength, at a heating time of 40 seconds, changeover time of 0.5 seconds, and a weld time of 40 seconds; total cycle time was 80 seconds. [525]

18.1.11.3 Weld microstructure

Microstructure of infrared welds is similar to that of hot tool welding. Three zones are present: large spherulites in the bulk material, a flow layer with deformed or elongated spherulites aligned in the direction of melt flow, and small spherulites in the middle of the weld. Due to rapid cooling of the weld, spherulites in the weld remain small and do not grow. Microstructural zones are shown in Figure 18.13. [525]

18.1.11.4 Equipment

Radiant heaters or lamps used in infrared welding include quartz-halogen, tungsten, nickel-chromium (Ni-Cr), and ceramic coated heating elements. Ceramic coated heating elements are used for lower temperatures; quartz and halogen radiators are used for higher temperatures, 1000–3000°C (1832–5432°F). Tungsten filaments produce intense radiation; however, they are only available in linear and spot shapes and are sensitive to pigmentation and formulation of the materials being welded. Ni-Cr heaters are available in different shapes, such as tubular, and can reach a temperature of 850°C (1562°F) in minutes, radiating energy of 2–5 μm in wavelength.

18.1.11.5 Applications

Infrared welding is a relatively new process. It has been used in sealing low and high density polyethylene in aseptic food packaging and joining polypropylene and polyvinylidenedifluoride (PVDF) in pressurized plastic piping. It is expected to find applications in the automotive, medical device, appliance, electrical, and construction industries. [523, 579, 524, 526, 538]

18.1.12 Laser Welding

Laser welding is a new process currently being developed, in which a high intensity laser beam is used to increase the temperature at the joint interface of thermoplastic materials to or above the melt temperature. The molten plastics cool and solidify, forming a weld. [567]

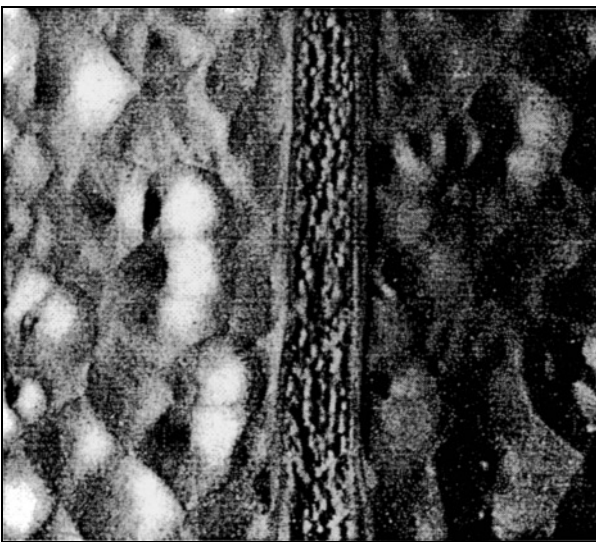


Figure 18.13 Micrograph of a polypropylene infrared weld showing the three weld zones. Large spherulites present in the bulk material are deformed near the weld due to melt flow. Small spherulites are present within the weld. Heating distance was 2.54 mm (0.10 in.), heating time was 11 seconds, changeover time was 0.8 seconds, and weld pressure was 0.44 MPa. Magnification is 50X.

18.1.12.1 Process

Carbon dioxide (CO_2) and Nd-YAG (neodymium ions in a medium of yttrium aluminium garnet) lasers are predominantly used in industrial applications. CO_2 lasers emit radiation at wavelengths of 9.2 to 10.8 μm , with the strongest emission at 10.6 μm , and range in power from 30 W to 40 kW. The laser beam is transmitted through air, reflected from mirrors, and focused using ZnSe lenses. In the Nd-YAG laser, flashlamps excite Nd^{3+} ions in a solid crystal rod, resulting in radiation with the strongest emission at a wavelength of 1.06 μm . The short-wavelength beam is transmitted through a fiber optic beam delivery system, and power ranges from 30 W to 2 kW. Lasers can generate radiation continuously (continuous wave), or light may be emitted in short bursts of microsecond or millisecond duration (pulsed); pulsed lasers are useful when overheating of the material is a problem. CO_2 lasers generally operate in a pulsed mode, while either pulsed or continuous wave modes can be used with Nd-YAG lasers. [567, 604]

In laser welding, parts being joined are clamped onto a moving table. Pressure can be applied throughout the process or may only be applied after heating is terminated. In the presence of a shielding gas, the high intensity laser beam travels at high speed across the weld interface of the parts being joined, cutting the weld interface and homogeneously heating the weld area. The diameter of the dot-like laser beam corresponds approximately to the wall thickness of the parts being joined. The beam causes heating that is localized near the joint interface that can rapidly result in melting, degradation, and vaporization of the polymer in the weld interface.

18.1.12.2 Processing parameters

Under optimum welding conditions, laser welding of polypropylene produced joints with strengths (33 ± 0.7 MPa) and elongations equal to the bulk material. In those cases, failure usually occurred outside the weld region. Among the welding parameters studied (power, beam offset from the focal point being on the tip surface of the specimen, shielding gas flow rate, welding pressure, and travel speed), laser beam offset (power density) and welding pressure showed the most significant effect on the joint strength. Increasing beam offset while decreasing power density increased the joint strength all the way to the highest offset tested. For polypropylene there existed an optimum pressure for

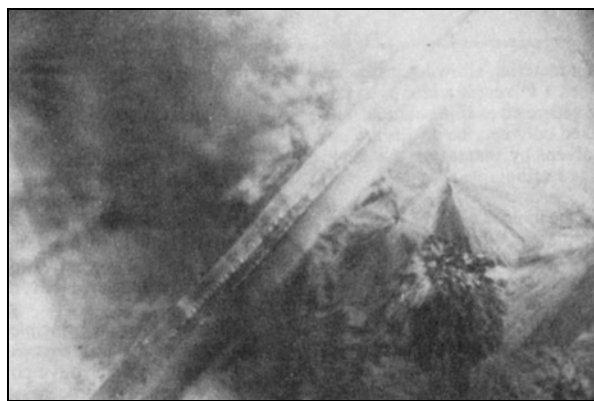


Figure 18.14 Transmitted polarized light micrograph of a polypropylene laser weld. Small spherulites can be observed near the weld interface; larger spherulites are present in bulk material. Magnification is 200X.

achieving the highest joint strength. The effect of power, travel speed, and shielding gas flow rate on joint strength was very small as long as the interface could be cut in one pass. Generally, laser welding of polypropylene was very fast and required no pre-welding preparations. [568, 567]

18.1.12.3 Weld microstructure

Laser heating is localized to the weld area, and the size of the heat affected zone, the area of the polymer that is affected by heat, is lower than in other welding methods. Figure 18.14 is a polarized light micrograph of laser welded polypropylene. Smaller spherulites can be seen near the weld and in the weld bead than in the bulk material, probably due to rapid cooling of the weld and bead. The weld interface appears to have an amorphous structure.

18.1.12.4 Applications

Low power CO_2 lasers have the capability of joining thin (<0.2 mm) plastic sheets in lap and cut/seal configurations at high speeds (50 m/min; Table 18.2).

18.1.13 Adhesive and solvent bonding

In adhesive and solvent bonding, a material different from either of the parts to be joined is applied to the joint surfaces. In solvent bonding, a solvent is used to dissolve the joint surfaces of plastic parts; the parts are then held together as the solvent evaporates, forming a bond. In adhesive bonding, an adhesive applied to a joint develops structural features as it cures, forming a bond to both joint surfaces. Adhesive bonding is the most general of all joining techniques and can be used to join plastic parts to each other or to dissimilar materials such as metals, ceramics, or wood. A

Table 18.2 Summary of laser weld conditions and tensile properties for polypropylene joints.

Material			Laser Conditions			Tensile Properties	
Type	Thickness (mm)	Joint type	Type	Power (W)	Speed (m/min)	% of parent	Failure mode
PP	0.2	lap	CO ₂	100	51	98	parent
PP	0.2	lap	Nd:YAG	80	0.2	70	weld
PP	2.0	butt	Nd:YAG	80	0.1	30	weld

range of bond strengths is available, ranging from low-strength putty and caulking compounds, which are used only for space- and void-filling, to high-strength structural adhesives used in the aerospace and aircraft industries.

18.1.13.1 Mechanism of bonding

In solvent bonding, solvent application softens the parts being bonded, allowing increased freedom of movement of polymer chains. Solvent applied to a non-crosslinked polymer such as polypropylene separates the polymer chains as if they were in solution. When the two solvent-softened parts are pressed together, molecules from each part come in contact. Van der Waals attractive forces are formed between molecules from each part, and polymer chains from each part intermingle and entangle. As the solvent evaporates, polymer chains become increasingly restricted in movement; after complete evaporation, polymer motions cease, and the amount of entanglement of polymer chains across the bond interface determines bond strength. In solvent bonding, the interaction between polymer and solvent must be maximized. Solvent application must be carefully controlled, since a small difference in the amount of solvent applied to a substrate greatly affects joint strength. Complete evaporation of solvent may not occur for hours or days. [650]

In adhesive bonding, attractive forces form between the adhesive and the adherends (the parts being joined). Types of attractive forces vary with type of adhesive and adherends but are generally a combination of adsorptive, electrostatic, and diffusive forces at the interface between adherend and adhesive. Attractive interfacial forces are very strong; adhesive forces are frequently stronger than the cohesive forces of the adhesive or adherend, and joint failure generally occurs in the adhesive or adherend, not at the joint interface. [644]

18.1.13.2 Adhesive Cure

Cure time and method are important in obtaining optimum joint strength. Although the classical

definition of curing a resin refers to the chemical crosslinking of a thermosetting polymer, a broader definition is used for the curing of adhesives. Adhesive curing generally refers to the process in which a polymer undergoes a change from the liquid to the solid (gel, rubber, or hard plastic) rheological state, regardless of the physical or chemical method used to induce the change. The method used to induce the liquid-to-solid conversion depends on the class of adhesive. For a thermoplastic adhesive, curing is the physiochemical process of cooling the molten polymer. Other curing processes involve chemical reactions; thermosetting adhesives (epoxies, polyurethanes) are cured through chemical crosslinking, while other adhesives, such as cyanoacrylates, cure by polymerization of a liquid monomer. [644]

Some adhesives cure by exposure to high temperatures; however, curing agents or initiators are usually necessary to begin polymerization or crosslinking reactions. Many adhesives cure by reaction with weak bases or anionic functional groups (water, amines, anhydrides, amides). Others require initiators or activators, such as peroxides, oxygen, ultraviolet light, or electron beams, in order to generate free radicals for a polymerization chain reaction. Other adhesives require metal salts, acids, or sulfur for cure reactions. Cures times range from a few seconds to several days.

18.1.13.3 Types of adhesives

A variety of materials are used as adhesives, including natural polymeric compounds (starches, dextrans, proteins, and natural rubber), inorganic materials (silicones), and synthetic polymeric materials (thermoplastics, thermosets, elastomers). Forms of adhesives include pastes, liquids, films, and foams. Adhesives can be classified as anaerobic, which must cure in the absence of air, or aerobic, in which the curing reactions are not inhibited by oxygen. Functional classifications include holding adhesives, such as masking tape, which hold parts together for limited amounts of time; instant

adhesives, which cure within seconds; structural adhesives, adhesives that can sustain stresses of at least 50% of the original strength of the part; one-part adhesives, such as rubber cement; and two-part adhesives, such as epoxies. [662, 644, 491]

Adhesives can be water-based, in which surfactants are used to disperse and stabilize polymer chains into small particles, solvent-based, or 100% solids. Most adhesives used in the U.S. are solvent-based, although use is declining due to environmental regulations. [529]

Most commercial adhesives are classified according to polymer composition. Major classes are described below.

Hot melt. Thermoplastics are frequently used as hot melt adhesives. They are applied to the adherends at a temperature much higher than the melting temperature of the thermoplastic, producing a low viscosity fluid that wets the adherend surface. The parts are then clamped, and the thermoplastic adhesive cools and resolidifies, forming a bond between the two substrates. Hot melt adhesives can form both rigid and flexible bonds and can fill gaps and irregularities between parts. Parts must be assembled quickly, before the molten material solidifies. Many hot melts do not possess good wetting properties. [621, 495, 655]

Hot melt adhesives include semicrystalline thermoplastics (polyamides and polyesters, for structural applications), polyethylene for general purpose bonding, polysulfones (high temperature applications), ethylene-vinyl acetate copolymers (low temperature applications), and polyesters. Some thermoplastics and elastomers are applied as one-part emulsions, polymers dispersed in an aqueous solvent, instead of as hot melts; vinyl acetate polymers are commonly used as household white glue. For most applications, one of the substrates must be permeable to allow water removal from the assembly. [644, 662, 655]

Acrylic. Acrylic adhesives are derivatives of acrylic acid esters. Long-chain acrylics, such as butyl methacrylate, are relatively soft; methyl methacrylate, with a short carbon chain, has a higher strength and modulus. Blends of short and long chains are also possible, allowing a wide range of flexibility in adhesive properties. Substituted acrylics, such as the cyanoacrylates, are highly reactive and cure within seconds of application. Acrylic adhesives can dissolve grease and wet contaminated surfaces. They are insensitive to

adherend surface preparation when compared to other glassy adhesives, such as epoxies. [655]

Curing occurs through polymerization, by free radical or anionic mechanisms. Free radical polymerization, a chain reaction, can be initiated by organic peroxides or other active oxygen compounds or by UV light. Polymerization with peroxide initiators requires elevated temperatures (60–100° C, 140–212° F) to occur at a significant rate; activators and catalysts are necessary for polymerization at lower temperatures. Activators, such as reducing agents, induce peroxides to initiate the reaction, while catalysts or accelerators (tertiary amines, polyvalent metal salts) increase the polymerization rate. Maximum operating temperatures are usually ~105° C (226°F), the glass transition of polymethyl methacrylate. [655, 644]

Acrylic adhesives include methacrylates, structural adhesives composed of elastomers and toughening agents dissolved in methyl methacrylate and other monomers, and second-generation acrylics, which contain dissolved polymers to reduce adhesive shrinkage and increase toughness. Cyanoacrylates are highly reactive cyanoacrylic esters that cure rapidly through anionic polymerization at room temperature, with trace amounts of water or amines as catalysts. Cyanoacrylates can be used for bonding difficult-to-bond plastics such as polyolefins if primers are first applied to the part surface. Primers or adhesive promoters are substances with chemical structures that promote strong adhesive properties (surface tension effects, dipole interactions) when applied in very thin films. They increase adhesion and improve shear, peel, and tensile strength. After evaporation of the primer solvent, the adhesive can be applied; depending on the type of plastic, bond strengths up to twenty times that of the unprimed strength can be obtained. Primers are active from 4 minutes to one hour after solvent evaporation. Cyanoacrylate bonds are frequently stronger than bulk material. [651, 655, 495, 644, 646]

Light-curing acrylics, composed of a blend of acrylic monomers, oligomers, and polymers, polymerize after exposure to ultraviolet light of a particular wavelength and intensity. They are one-part, solvent-free adhesives available in a wide range of viscosities, from 50 cP to thixotropic gels. Cure times generally range from 2 to 60 seconds. Anaerobic adhesives are one-part adhesives composed of dimethacrylate monomers (esters of alkylene glycols and acrylic or methacrylic acid) that cure

only in the absence of air. They are less toxic than other acrylics, have a mild, inoffensive odor, and are not corrosive to metals. [646, 644, 655]

Epoxies. Epoxy adhesives are polymers that contain epoxy groups in their molecular structure. Epoxies are usually supplied in the form of liquids or low melting temperature solids, and most contain additives that influence the properties of the material — accelerators, viscosity modifiers, fillers, pigments, and flexibilizers. Flexibilizers reduce sensitivity to localized regions of high stress by reducing the elastic modulus of the bonded assembly. [495, 655, 662] .

Depending on the epoxy, cure can take place at room or elevated temperatures. Two-part epoxies must be mixed just before curing with stoichiometric amounts of amine or anhydride-containing substances. The rate of cure may be increased by adding accelerators to the reaction mixture or by a temperature increase. Heat cured adhesives generally have better mechanical strength than room temperature-cured epoxies. One-part solid epoxies combine epoxy polymers with a curing agent; bonds are rigid and strong, with low peel strength. In epoxy films, a thin film of epoxy and a high temperature curing agent such as an aromatic amine is coated onto release paper. For bonding, the film is cut to the required shape and applied to one of the adherends. Bonds are temperature resistant and brittle and exhibit low peel strength. [644, 655, 662]

Elastomers. Natural and synthetic, high molecular weight rubbers or elastomers, dissolved in either hydrocarbon or chlorinated hydrocarbon solvents, are used as adhesives to produce bonds with high peel strength but low shear strength compared to glassy adhesives. They are used when high peel strength is required, such as when bonding a large flexible panel to a rigid composite panel, or as contact adhesives (neoprene or nitrile elastomers), which do not require pressure for

bond formation, to bond decorative films onto exterior panels. [655, 644, 664,]

Adhesives suggested for use in bonding glass fiber filled polypropylene (Hoechst Hostacom) are given in Table 18.3. [326]

18.1.13.4 Surface preparation methods

Because it is a chemical joining process that occurs on the surface, adhesive bonding is very dependent on surface preparation of adherends and the technique used for handling, applying, and curing the adhesive. Surface preparation of the joint is necessary for optimum attraction and joint strength. Joint surfaces should be rough, in order to more effectively trap adhesive molecules that bounce across the surface, and free of contaminants that would interfere with the forces of attraction.

Surface preparation cleans the adherend surface and/or introduces chemical functional groups at the surface to promote wetting and chemical bonding between the adherend and adhesive. Contaminants include grease, dust, and oil. Generally, surface treatments can be mechanical, chemical, or electrical. Newer treatments use UV light or lasers for surface modification. Cleaning order consists of an initial solvent cleaning, followed by abrasion or a chemical surface alteration. Solvent cleaning is then repeated. [644]

Nonpolar polymers such as polypropylene are relatively inert and chemically resistant and are difficult to bond. No surface attack takes place at room temperature on molded parts in contact with solvents, so that unless the surface is pretreated, only pressure-sensitive adhesives can be used. Surface pretreatment increases joint strength considerably. Polypropylene generally requires extensive surface preparation to oxidize the surface and introduce polar reactive groups. Suggested surface preparation methods for glass fiber-reinforced polypropylene (Hoechst Hostacom) are: a primer (Herberts R 47 509), flame treatment with a very oxygen-rich burner flame, corona discharge, and dipping in a chromosulfuric acid bath. Several surface preparation methods applicable for polypropylene are described below. [653]

Etching or Oxidation. Ammonium peroxydisulfate, chlorine, ozone, perchlorous and perchloric acid, permanganate, and, most commonly, chromic acid are used to oxidize the surface of plastics. Reactive groups, such as hydroxyl, carbonyl, carboxylic acid, and sulfate, are introduced, and cavities are formed to provide sites for mechanical inter-

Table 18.3 Adhesive systems for bonding parts made from Hostacom polypropylene

Type of adhesive	Basis
Pressure-sensitive adhesives	pressure-sensitive adhesive solutions. pressure-sensitive adhesive dispersions.
Contact adhesives	synthetic rubber, polyurethane.
Two-pack adhesives	epoxy resin, polyurethane, phenolic resin/synthetic rubber
Hot-melt adhesives	vinyl copolymers.

locking of substrate and adhesive. Increases in reaction time and temperature increases the depth of etching with polypropylene. [647, 653]

Surface grafting. A chemical species can be grafted onto the substrate surface to increase adhesion. [647]

Thermal treatment. Exposing the plastic to a blast of hot air ($\sim 500^{\circ}\text{C}$, 932°F) oxidizes the surface of the plastic by a free radical mechanism, introducing polar groups (carbonyl, carboxyl, amide, and hydroperoxide) that increase wettability. Cross-linking also occurs, and interfacial diffusion during bonding is enhanced by chain scission. Thermal treatment is similar to flame treatment. [647]

Primers. Primers are applied to part surfaces before bonding. Solvent is flashed off, leaving the reactive chemical species on the surface. Primers form a chemical bridge between substrate and adhesive through multifunctional groups that react preferentially with either adhesive or substrate. Polyolefin surfaces can be bonded immediately. [647]

Corona discharge. Corona discharge occurs when an electrode at a high electric potential ionizes the gas surrounding it. The gas discharges the potential. If a plastic film is passed between the high-potential electrode and a grounded electrode, some of the ionized gas particles will undergo chemical reactions with the plastic surface, introducing reactive groups to the surface and increasing surface roughness. Groups such as carbonyls, hydroxyls, hydroperoxides, aldehydes, ethers, esters, carboxylic acids, and alkenes have been proposed as the reactive species. Corona discharge is usually performed at atmospheric pressure in air, which oxidizes the surface, although nitrogen is sometimes used as the ionizing gas. Polyethylene and polypropylene are treated using an electrical potential of 15 kV at 20 kHz. [653, 647]

Plasma discharge. In plasma discharge, a gas (oxygen, argon, helium, air) at low pressure (0.1–1.0 torr) is excited by applying radiofrequency energy to a pair of electrodes. Electrons are stripped from the gas particles, producing free radicals at high energy levels. Excited gas particles at higher energy levels fall to lower energy levels, resulting in emission of radiation in the UV and far-UV ranges. The characteristic glow obtained in plasma discharge is similar to that of neon bulbs, fluorescent bulbs, and lighting. When the part is placed in the low pressure chamber, water, oils, and other organic materials are removed from the part surface by free radicals. Plasma treatment reacts to a depth of 0.01–0.1 μm

and reduces the contact angle of the substrate, increasing wettability. [652, 647, 653]

A liquid adhesive on a polypropylene surface is shown in Figure 18.15, before and after plasma treatment. Before treatment, the adhesive beads on the surface; after plasma treatment, it spreads out. Substrates should be bonded immediately following plasma treatment. [652, 647, 653]

Laser treatment. Laser treatment of polypropylene and polyethylene, using XeCl, ArF, and KrF lasers introduces oxygenated functional groups to the surface and removes surface contaminants. [624]

Surface treatment of polypropylene and glass-reinforced polypropylene (GRPP) by ArF, XeCl, and KrF lasers resulted in increased bond strength. A cyanoacrylate adhesive was used with single lap shear joints; control joints were degreased and treated with primers prior to bonding. Bond strengths at optimum frequencies were higher with laser treatment than with the control samples. [624]

Transcrystalline growth. In transcrystalline growth, substrates are molded against a high energy metallic substrate that causes crystallites to form on the plastic surface. Rod-like or columnar spherulites form inward from the plastic-metal interface, and low molecular weight material is driven into the plastic interior. Oxidation of the plastic surface may also occur, increasing wettability. Molding conditions, such as the cooling rate and mold surface, are important in determining the effectiveness of this treatment. [647]

Ultraviolet radiation. UV radiation at particular wavelengths causes chain scissions, crosslinking, and oxidation of the part surface. Surface changes are dependent on the wavelength of light used. [647]

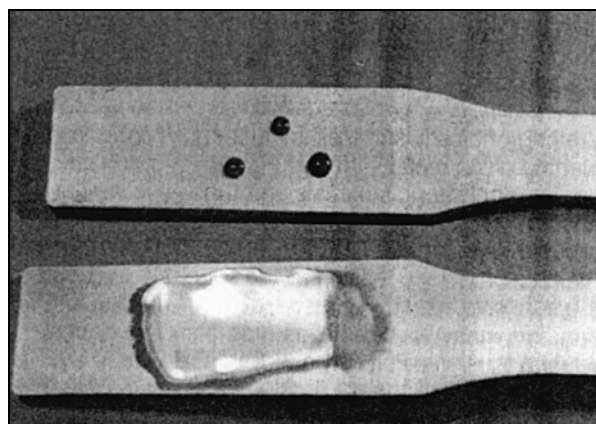


Figure 18.15 The effect of plasma treatment on wettability. Before plasma treatment, top, the adhesive beads on the substrate surface. After plasma treatment, bottom, adhesive spreads out, coating the surface.

Flame treatment. A brief exposure to flame oxidizes the surface of plastics through a free radical mechanism, introducing hydroxyl, carbonyl, carboxyl, and amide groups to the part surface. Chain scissions and crosslinking also occur, increasing wettability and interfacial diffusion during bonding. Flame treatment affects the part to a depth of about 0.004–0.009 μm . [647]

Removal of surface layers. High energy ion beams or radio-frequency plasma discharges can be used to etch the surface and remove surface layers, including surface contamination. A roughened, textured surface is produced for bonding. [653]

18.1.13.5 Joint design

Joint design in adhesive and solvent bonding is an important determinant in the strength, reliability, and durability of the bond. The most effective joint design for a particular application depends on the stresses the part will encounter and the mechanical properties of the adhesive and adherends.

The joint must accommodate all loads on the part. For structural joints, the load in one adherend must be transferred through the adhesive layers to the other joint component. Higher strength is generally obtained by larger bond surface areas. A lap joint or lap combination joint provides maximum surface area for bonding. In T-joints and butt joints, the bond area is limited by the wall thickness of the part; these joints are not recommended for solvent and adhesive bonding. For joining curved surfaces, each surface should have the same radius in order to provide uniform contact over the entire joint area. [622, 647, 643, 655, 644]

The stress distribution on the adhesive affects the ability of the joint to accommodate loads. Joint design should strive to distribute the stresses equally over the bond area in order to create uniform stress on the adhesive. Adhesive bonds subjected to tensile, compressive, or shear stress during loading experience a more uniform stress distribution than bonds exposed to cleavage or peel stress. Compressive strength of most adhesive films is greater than tensile strength; optimal joint design should maximize compression and minimize tensile stresses. The stress distribution of a cleavage or peel stress is concentrated at one end of the joint. Peel strength of any adhesive may be as low as 1% of its shear strength; low-modulus, elastic adhesives usually have higher peel strength. Joint design should ensure that peel and cleavage

stress are minimized and shear stress is maximized. [647, 655]

18.1.13.6 Polypropylene adhesive bond strength

A study was conducted to test for bond strength on a representative matrix of commonly used plastics and the adhesives best suited to them. The effect of polymer composition on bond strength was evaluated by compounding plastic formulations with each of the most commonly used additives and fillers for that plastic; common grades were used for the remaining resins. The effect of each additive and filler was determined by comparing the bond strength achieved with the specially compounded formulations to that of the neat plastic. In addition, the effect of surface roughening and chemical treatment of the plastic surface on bond strength was examined. Results for polypropylene are given in Table 18.4.

The block-shear (ASTM D 4501) test was chosen as the test method because it places the load on a thicker section of the test specimen that can withstand higher loads before experiencing substrate failure. In addition, the geometry of the test specimens and the block-shear fixture help minimize peel and cleavage forces in the joint. How well the block-shear test method reflects the stresses that an adhesively bonded joint will experience in real world applications should be considered. Also, limitations on the data due to the variety of additives and fillers used by different companies should not be ignored.

Prism 401, used in conjunction with Prism Primer 770, achieved the highest bond strengths on PP, typically substrate failure. Black Max 380, a rubber toughened cyanoacrylate adhesive, Prism 401 and Super Bonder 414, both cyanoacrylate adhesives, Depend 330, a two-part no-mix acrylic adhesive, and Loctite 3105, a light curing acrylic adhesive, all performed poorly on unprimed, un-abraded PP.

The use of Prism Primer 770, in conjunction with Prism 401, resulted in a dramatic, statistically significant increase in the bond strengths achieved on PP, typically substrate failure. Surface roughening resulted in either no effect or a statistically significant increase in the bond strengths achieved on PP.

Polypropylene is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and ODC Free Cleaner 7070.

Table 18.4 Shear strengths of PP to PP adhesive bonds made using adhesives available from Loctite Corporation. Values are given in psi and (MPa).^{a,c}

		Loctite Adhesive					
Plastic Material Composition (Himont Profax 6323)		Black Max 380 rubber toughened cyanoacrylate (200 cP)	Prism 401 surface insen- sitive ethyl cyanoacrylate (100 cP)	Prism 401 Prism Primer 770 polyolefin primer for cyanoacrylate	Super Bonder 414 general purpose cyanoacrylate (110 cP)	Depend 330 two-part no- mix acrylic	Loctite 3105 light cure acrylic (300 cP)
Unfilled resin	5 rms	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
Roughened	26 rms	50 (0.3)	550 (3.8)	1300 (9.0)	300 (2.1)	200 (1.4)	450 (3.1)
Antioxidant	0.1% Irganox 1010 0.3% Cyanox STDP	50 (0.3)	250 (1.7)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
UV stabilizer	0.5% Cyasorb UV 531	50 (0.3)	50 (0.3)	>1950 ^b (13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
Impact modifier	9% Novalene EPDM	50 (0.3)	150 (1.0)	>1650 ^b (>11.4) ^b	200 (1.4)	200 (1.4)	100 (0.7)
Flame retardant	9% PE-68 4% Antimony oxide	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	250 (1.7)
Smoke suppressant	13% Firebrake ZB	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
Lubricant	0.1% Calcium stearate 24-26	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
Filler	20% Cimpact 600 Talc	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	100 (0.7)	200 (1.4)	100 (0.7)
Colorant	0.1% Watchung Red RT-428-D	50 (0.3)	50 (0.3)	>1950 ^b (>13.5) ^b	50 (0.3)	200 (1.4)	100 (0.7)
Antistatic	0.2% Armostat 475	50 (0.3)	200 (1.4)	>1950 ^b (>13.5) ^b	200 (1.4)	200 (1.4)	100 (0.7)

^a All testing was done according to the block shear method (ASTM D4501).

^b Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

^c For more information on data presented in this table, contact Loctite Corporation at 800-562-8483 (1-800-LOCTITE). Request the "Design Guide for Bonding Plastics."

18.1.14 Mechanical Fastening

Mechanical fastening is a simple and versatile joining method. Mechanical fasteners are made from plastics, metals, or a combination of the two materials and can be periodically removed and replaced or reused when servicing of the part is necessary. Screws, nuts, and inserts can be made of plastic or metal; rivets are generally made from metals. Plastic fasteners are lightweight, corrosion resistant, and impact resistant. They do not freeze on threads of screws and require no lubrication. Metal fasteners provide high strength and are not affected by exposure to extreme temperatures. [680]

Screws, nuts, washers, pins, rivets, and snap-type fasteners are examples of non-integral attachments, in which the attachment feature is a

separate part. Use of separate fasteners requires plastic materials that can withstand the strain of fastener insertion and the resulting high stress near the fasteners. Snap-fits are examples of integral attachments, attachment features that are molded directly into the part. Strong plastics that can withstand assembly strain, service load, and possible repeated use are required for non-integral attachments. Separate fasteners add to product cost due to increased assembly time and use of additional material and can be difficult to handle and insert; as a result, use of integral attachment features is increasing. [579, 678, 687]

Different types of mechanical fasteners are described in the following sections.

18.1.14.1 Machine screws and nuts, bolts, and washers

Parts joined using machine screws or screws with nuts can be disassembled and reassembled an indefinite number of times. Tensile stress should be avoided in assembly design; compressive stress is more desirable due to a lower susceptibility to stress cracking and crazing. [416]

Machine screws and bolts used in joining plastic parts should have a flat side under the screw head. Flat head screws, with conical heads, produce potentially high tensile stresses due to wedging of the screw head into the plastic part. Screws with flat undersides, such as the pan head screw, do not undergo this wedging action, and the stress produced is more compressive. Flat washers distribute the assembly force and should be used under the fastener head. [502, 640]

Screws or threaded bolts with nuts pass through the plastic part and are secured by an external nut or clip on the other side. For compressive rather than tensile loading, space between surfaces of parts being assembled should be eliminated, using spacers if necessary. Some part designs may require a loose-fit gap between bosses to prevent high bending stresses or distortion as the parts go into compression. [78, 639, 430]

18.1.14.2 Self-tapping screws

Self-tapping or self-threading screws cut or form a mating thread in a preformed hole of a plastic part. No nuts are used, and access is needed from only one side of the joint. No clearance is required, since the mating thread fits the screw threads. Only a drilled or molded pilot hole is required, and installation is rapid. Self-tapping screws are widely

used due to an excellent holding force and lower stress production than some of the other fastening methods. [629, 678, 639, 676]

The two basic classes of self-tapping screws for thermoplastics are thread-forming screws and thread-cutting screws. Thread-forming screws form threads in the plastic by displacing and deforming plastic material, which flows around the screw heads. No material is removed, which creates a fit with zero clearance and produces large internal stresses. Thread-forming screws are inexpensive and vibration resistant. They are recommended for structural foam parts. Although they can provide acceptable performance in solid-wall parts, they should be used with caution in non-foam materials due to the possible generation of highly stressed regions. Multiple assemblies and disassemblies are possible with thread-forming screws. [678, 674, 118]

Thread-cutting screws have a sharp cutting edge; as the screw is inserted, plastic chips are removed. Depth of the preformed hole should be slightly longer than the screw depth in order to provide a depository for the plastic chips. High internal stresses are avoided in thread-cutting screws due to removal of material during installation. Stress relaxation of the plastic with temperature changes and time has only a minimal effect on screw performance. Only a minimum number of reassemblies are possible; repeated removal and reassembly may cause new threads to be cut over the original thread, resulting in a stripped thread. For repeated assembly, the screw should be carefully inserted into the original thread by hand, or Type 23 screws (Figure 18.16) should be used initially and replaced with a standard machine screw for reassembly. Thread-

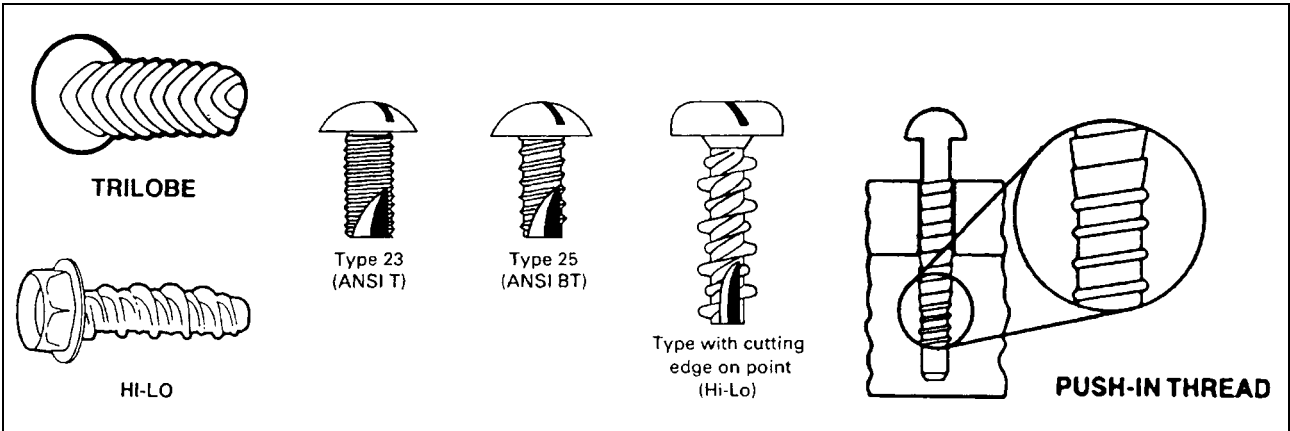


Figure 18.16 Common types of self-tapping screws.

cutting screws provide acceptable performance in solid-wall parts but are not recommended for structural foam. [640, 678, 674, 78, 676]

Different types of thread-forming and thread-cutting screws are available for particular applications. The most widely used self-tapping screws for thermoplastics are the Type B, Type BT, Hi Lo, and Trilobe or Plastite. Type B, a thread-forming screw is otherwise identical to Type BT, a thread-cutting screw (Figure 18.16). The Hi Lo is a double-lead screw, available as either thread-forming or thread-cutting; the Trilobe is a thread-forming screw with triangular-shaped threads. [674]

18.1.14.3 Inserts

Inserts are plastics or metals that are inserted into another material. They are commonly used for applications that require frequent disassembly, or when a limited engagement length prevents the use of screws. They are used for structural foam and other materials with low shear strengths that cannot withstand fastener loads alone. Threaded inserts are available in internal thread sizes from 4-40 to 1/4–20 (inches) or M2 — M6 (metric). Various lengths are available in each size for different depths. Performance of inserts is dependent on the shear strength of the material and the knurl pattern on the outer surface of the insert. [674, 678, 501]

Molding inserts directly into the part during the injection molding process is a convenient and popular method of insert application. Molded-in inserts provide an anchor for machine screws and are commonly made from metals such as steel, brass, and aluminum. Inserts are placed on core pins in the mold, and the plastic part is then molded around them in the mold cavity. Molding in inserts does not require a secondary insertion operation and provides higher torque and pull-out properties than other insertion methods; however, high stresses are created in the areas around the inserts. [623, 122, 678]

Molded-in inserts are not recommended for use with some plastics because of the high stresses produced. Molded-in inserts perform better in higher creep, crystalline polyolefins than with rigid amorphous resins. Molded-in stresses result in high failure rates in the form of cracking in low creep materials. [623, 500]

Processing conditions can affect the quality of the molded-in insert. In experiments with polypropylene homopolymer, the pull-out resistance of molded-in inserts was sensitive to changes in injection

pressure, injection time, and insert temperature. Increases or decreases in injection pressure or injection time from the optimum values, with all other processing parameters identical, significantly decreased holding power in tensile tests. Increasing the insert temperature to 95°C from 22°C reduced the load required to pull the insert out of the surrounding plastic material by 19 kg. [681]

Holding power was dramatically reduced when internal lubricants (epolene wax, calcium stearate) were used in molding. Lubricants were present at loading levels recommended by the manufacturers. The pull-out load for inserts in polypropylene decreased by 29 and 37 kg in the presence of epolene wax and calcium stearate, respectively. Lubricants caused the inserts to slip out of the plastic more easily. Mold Wiz lubricant did not affect pull-out resistance as dramatically; the decrease in load required for pull-out was 9.5 kg. [681]

Expansion inserts have longitudinal slots that collapse on installation to allow the insert to enter the preformed hole. Once in place, the insert can be expanded by either a spreader plate incorporated into the insert or by the action of the assembly screw. Because these inserts absorb much of the assembly force, they are used in plastics that cannot withstand a high level of stress. [679, 495]

Self-tapping inserts have coarse threads and longitudinal slots or notches that cut into the plastic material. When the insert is screwed in, a corresponding thread is produced in the plastic. Self-tapping inserts provide high pull-out resistance but poor torsional resistance. [495]

Thermal inserts are heated before insertion into the plastic material. The heated insert softens the plastic, which then flows around the outer surface of the insert. Thermal heating can occur by direct contact with a hot body or by preheating in a temperature-controlled chamber. Installation equipment is inexpensive, but insertion is slow. [674, 495]

18.1.14.4 Press or interference fits

In press or interference fits, a shaft of one material is joined with the hub of another material by a dimensional interference between the shaft outside diameter and the hub inside diameter. Press-fitting is an economical procedure that requires only simple tooling, but it produces very high stresses in the plastic parts. It can be used to join parts of the same material as well as dissimilar materials. [118, 500, 78]

Maximum pull-out forces are obtained in press fits by using the greatest allowable interference

between parts that is consistent with the strength of the materials. Allowable interference is dependent on the properties of the materials, part geometry, and environmental conditions. Interference limits are determined for a part design to ensure that the hoop stress produced in the parts does not exceed the maximum allowable stress for the plastic. [629]

The high stress produced in press fit assembly can make the parts more susceptible to chemical and thermal attack. To reduce stress concentrations, parts and inserts should be clean and free of all incompatible chemicals. Inserts with smooth, rounded surfaces produce less stress than knurled inserts, and knit lines should not be located in areas of the part that are being inserted. [500, 502, 78]

18.1.14.5 Snap-fits

In snap-fit fastening, two parts are joined through an interlocking configuration that is molded into the parts. Many different configurations are possible to accommodate different part designs. In snap-fits, a protrusion on one part (hook, stud, bead) is briefly deflected during joining to catch in a depression or undercut molded into the other part. The force required for joining varies depending on the snap-fit design. After the brief joining stress, the joint is vibration resistant and usually stress-free. [502, 675, 78]

Snap-fitting is an economical, rapid, and popular assembly method. Snap-fits can be used to join dissimilar plastics or plastics to metals and can be designed for permanent fastening or for repeated disassembly. Hermetic or moisture-resistant seals are possible in some designs. Snap-fits require more attention to engineering design than other mechanical fastening methods and can fail before or during assembly or during use if not designed properly. Stress analysis of some snap-fit designs can be performed using hand calculations; designs with more complicated geometries may require finite element analysis for accurate results. [579, 690]

The most common type of snapfit is the cantilever beam. A cantilever beam snap-fit is a hook and groove joint, in which a protrusion from one part interlocks with a groove on the other part (Figure 18.17). Cantilever beam snap-fits can be straight or may have a bend in the beam (curved beam). Rectangular cross-sections are common; beam cross-sections may also be square, round (hollow or filled), trapezoidal, triangular, convex, or concave. The beam can be of constant width and height or can be tapered to avoid stress con-

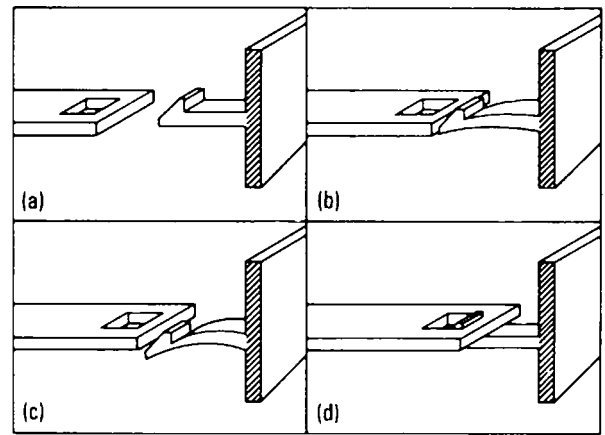


Figure 18.17 A cantilever beam snap-fit. a) A cantilever beam and mating piece before assembly. b) The latch is partially deflected as initial contact is made. c) The latch approaches maximum deflection. d) The latch locks into the hole in the mating part and returns to its undeflected position.

centration near the point of attachment with the part wall. [675, 502]

Cantilever snap-fits are easy to assemble and provide good retention. They undergo flexural stress during assembly and are modeled as cantilever beams in design calculations. After assembly, joints are usually stress-free; however, joints can be designed to be partially loaded after assembly for an extra-tight fit. Loaded snap-fits may be subject to creep or stress relaxation. [629, 690]

Other types of snap-fits include annular, used to join spherical parts, torsional, in which a latch is attached to a torsion bar or shaft; ball and socket snap-fits, used to transmit motion; and U-shaped snap-fits, commonly used for lid fasteners. Combinations of different types are also possible in one design.

Some design considerations in snap-fits include the forces required for assembly (and disassembly, if required), ease of molding and assembly, the material strain produced during assembly, and other requirements of the application. Stress analysis, based on a geometric model for the particular type of snap-fit, is performed to determine assembly forces, deflections, and stresses produced during assembly. [579, 675]

Snap-fits are used in a variety of industries to assemble power tools, computer cases, electronic components, toys, automobile parts, medical devices, washing machines, pens, bottles, and packaging boxes. Snap-fits can be used as a temporary holder for other assembly methods, such as adhesive bonding or welding. [690]

18.1.14.6 Staking

In staking, a head is formed on a plastic stud by cold flow or melting of the plastic. The stud protrudes through a hole in the parts being joined, and staking the stud mechanically locks the two parts together (Figure 18.18) [681]

Staking can be performed by four different methods: ultrasonic staking, cold staking, heat staking, and thermostaking. Cold staking or heading uses high pressures to induce cold flow of the plastic material; pressures of at least 41 MPa (6000 psi) are generally required. Stud lengths are approximately 1.5 times the stud diameter; stud length includes part thickness. Because cold heading creates high stresses on the stud, only more malleable thermoplastics are suitable for this process. Soft, brittle, or fragile materials are not usually assembled by cold staking. [681]

In heat staking, heated probes and light to moderate pressure are used to compress and reform the stud. Because stresses are lower than in cold staking, heat staking can be used to join a variety of plastic materials; polypropylene is commonly used for heat staking. Heat staking is used to join two parts of the same plastic or dissimilar plastics. It is an economical process that produces consistent results. [677, 681]

Thermo-pneumatic staking or thermostaking uses a heated, hollow tool to deliver a low volume of superheated air to the plastic stud. The tool is

lowered over the stud, and the hot air rapidly softens the plastic. The hot air flow is then shut off, and a cold stake probe located at the top of the tool descends onto the stud. A stud head is formed, and, after the plastic solidifies and cools, the cold staking probe is retracted. [681, 495]

In ultrasonic staking, a thermoplastic stud is melted and reformed to mechanically lock another, usually dissimilar material in place. A thermoplastic stud protrudes through a hole in the dissimilar material, usually metal; ultrasonic energy melts the stud, which compresses under pressure from the horn and takes the shape of the horn cavity. After vibrations stop, the horn remains in contact with the stud until it solidifies. Ultrasonic staking works well with soft or amorphous materials having low melt flows, allowing the head of the rivet to form by both mechanical and thermal mechanisms. With high melt materials or materials that require high vibrational amplitudes, melt can flow so rapidly that it is ejected out of the horn contour, resulting in an incomplete rivet head. [532, 619]

18.2 Decorating

Plastics decorating involves the modification of a plastic surface, using a coating or impression, by the application of heat, pressure, or a combination of both. Several decorating techniques are described below.

18.2.1 Appliqués

Appliqués are surface coverings applied using heat and pressure for a specified period of time; they may be applied as decals, during molding, or by hot stamping, hot transfer, or water transfer.

18.2.1.1 Decals

Decals are decorations or labels printed on carriers such as paper or plastic with a pressure sensitive adhesive backing. The decal is pressed into place on the plastic part when the backing is removed. Decals require a clean surface, free of mold release agents, with minimal sink marks and projections, and the adhesive backing must be compatible with the plastic. Gate marks should be hidden, and sharp corners should be broken to 0.5 mm (0.020 in.).

18.2.1.2 Hot stamping

In hot stamping, a pigmented, metallic or wood grain foil is placed between an etched metal or rubber die and the plastic surface. The etched pattern is

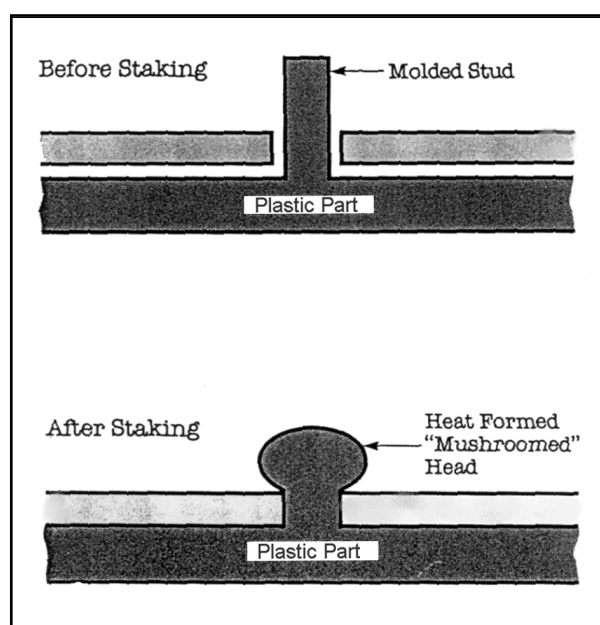


Figure 18.18 Staking. A plastic stud protruding from the part is softened by heat or forced to cold flow by high pressure, forming a mushroomed stud head that locks the parts together.

the reverse of that desired on the plastic. Heat, pressure, and a specific dwell time is then applied to stamp the pattern onto the surface. Foils are multi-layer laminates whose composition depends on the physical properties of the foil material (mar and chemical resistance, color) and properties of the plastic material (melt profile, surface characteristics). Foils are usually developed for the particular plastic and sometimes for the particular grade.

18.2.1.3 Hot transfer

In hot transfer, a dry coating is transferred to the plastic surface through a heated die; however, in this method, the die is flat, while the carrier contains the decorative pattern.

18.2.1.4 Water transfer

In water transfer, a flexible, water-soluble carrier film with an imprinted pattern is floated, ink side up, on the surface of a water bath. The plastic part is then dipped into the bath, and the film conforms to the shape of the part. After removal of the part, the film washes off, and a transparent coating is applied for abrasion resistance. Water transfer is used for patterns with no definite orientation (wood grain, marbling) and can be used on curved, contoured, and rough surfaces and around corners. The method requires a clean surface; application of a primer before decorating improves adhesion and properties. Projections on the part must be minimized, and no holes should be present.

18.2.1.5 In-mold decorating

Parts can be decorated during molding by placement of a predecorated carrier into the mold; the molten plastic then fuses with the film during processing. Carriers must have good thermal stability due to the high temperatures encountered in injection molding. There should be no sharp edges, and complex surfaces may result in problems caused by air entrapment or stretching of the film.

18.2.2 Coloring

Colors can be blended or molded into the plastic resin; parts with contrasting outlines are produced with two molding sequences — one shot to provide a frame or core and the second for the complementary color. In two-color molding, sharp corners and edges should be minimized. The same material should be used for both part elements, and cycle time between molding of the two parts should be minimized.

Surfaces can be dyed by immersion of the part into the dye. Dyeing is an economical process, useful if abrasion resistance is unnecessary; however, uniformity is hard to control, and the maintaining of outlines is poor. Clean surfaces are necessary, with uniform walls and well-rounded edges for projections.

18.2.3 Painting

Parts can be painted to provide color for color matching, a high gloss or matte finish, a wood grain, luminescent or metal flake appearance, a textured appearance, or coverage of surface imperfections. Paints and coatings can also provide enhanced performance properties such as improved chemical, abrasion, or weathering resistance and electrical conductivity. Painting requires clean surfaces, and the paint should be compatible with the substrate. Parts should have uniform walls, and molding should be stress-free.

18.2.4 Metallization

Plastic surfaces are metallized to give the material surface a metallic appearance and make its properties more similar to that of a metal. Conductive paints composed of pigments and conductive particles (nickel, copper, silver, graphite) can be applied to the part with air atomizing or airless spray equipment. In electroplating, electric current is used to deposit metals from a metal salt solution onto a plastic rendered conductive by electroless plating.

Flame/arc spraying uses a jet of compressed air to atomize molten metal particles, obtained by melting metal wires with an electric arc, and spray them onto the part surface. In vacuum metallizing, the metal is heated in a vacuum chamber to its vaporization point, which is lower than the melt temperature of the plastic. The metal vapor then condenses on the cooler plastic surface.

Sputtering is a process in which metal atoms are dislodged by contact with an inert gas plasma instead of by heating the metal. In cathode sputtering, the metal is attached to the cathode, with the plastic acting as the anode. An electron beam dislodges positively charged metal ions, which then condense on the plastic surface. Ion plating is similar to sputtering, but inert gases are also used, in order to enhance adhesion from a chemical reaction of the inert gas plasma and the substrate.

Metallizing makes surface flaws more apparent, and the resin's physical characteristics may change. Clean surfaces are required, with no mold

release agents present, and pre-cleaning processes should be checked for compatibility. Design considerations include:

- uniform wall sections
- radiused sharp edges and corners (0.5 mm; 0.020 in. minimum)
- avoidance of deep vertical walls
- gradual wall transitions
- minimal amount of projections
- avoidance of flat areas
- hole depth of a diameter ratio less than 5 to 1
- recesses less than 5.1 cm (2 in.) with greater than 5 degrees draft
- minimum wall thickness about 2.0 mm (0.080 in.)
- maximum walls ranging to 4.8 mm (0.190 in.)

18.2.5 Printing

In printing, a mark or impression is made on a plastic surface. Printing processes include pad transfer, screen printing, laser printing, dyeing, and fill and wipe. In fill and wipe processes, the part is etched, and ink is used to fill the recesses. Excess ink is then wiped away. For sharp detail, the surrounding surface should be very smooth, and edges should be sharp. Adjacent surfaces should be polished. Thick rather than thin borders should be used, and inside corners should be radiused. Recesses should be 0.38 to 0.76 mm (0.015–0.030 in.) deep; small character openings may not be filled in.

Pad transfer is used to print on flat or irregular surfaces. A metal plate with an etched pattern is covered with ink, and a soft silicone rubber pad is pressed onto it. The pad picks up the ink pattern (in reverse) and is pressed against the part. The pad can wrap 180° around a small part (360° with specialized equipment), and coverage is excellent. Parts for pad transfer decorating should be designed with smooth and even transitions, and sharp edges and projections should be avoided. The surface finish affects sharp line intersections, and thickness can be inconsistent in large print areas. The size of the printing area should be minimized.

In screen printing, a pattern is produced by selectively sealing holes in a fine mesh screen. The screen is then placed on the part, and a squeegee is used to force ink through the open holes onto the part surface. Parts should be designed with smooth and even transitions, with all coverage areas in one plane, and points and projections should be avoided.

In diffusion processes (wet or dry), dye solids are transferred below the surface of a plastic (to a depth of 0.025–0.100 mm; 0.001–0.004 in.) using heat or heat and pressure. Inks used in this process undergo sublimation — they change from a solid to a gas and back without passing through the liquid phase. In wet diffusion, pad transfer methods are used to transfer the inks from a solvent suspension, which evaporates after exposure to heat, to the plastic substrate. Dry diffusion is similar to hot stamping; designs are reverse printed on a carrier, then applied to the surface by heat and pressure over a period of time. Wet diffusion is more economical; however, dry diffusion can transfer multiple colors in one operation.

Since dye inks are translucent, diffusion is appropriate only for light colored surfaces. Diffusion methods are limited to parts having planar or slightly curved surfaces, and the surface finish affects sharp line intersections. Wall sections should be thick enough to be stable during the heating process of dry diffusion.

Laser printing uses a CO₂ or YAG laser to produce marks on the surface. The laser beam vaporizes the plastic surface, changing the color. It is useful for permanently coding parts too small for conventional printing processes. Pulse power, rate, and marking speed control the depth of etching; the amount of contrast produced is important in determining the quality of the finish. Design considerations include gradual wall transitions and a minimization of sink marks.

18.2.6 Other processes

Textures and lettering can frequently be molded into the surface of the part, in order to hide surface imperfections and provide decoration at no additional cost. Additional draft is required to eject a part with textured sides. Surfaces with molded-in texture do not usually maintain optical clarity.

Another special process is flocking, in which the surface is coated with an adhesive and exposed to an electrostatic charge. Short textile fibers are then blown onto the surface and stand on end due to the charge. As in other processes, flocking requires clean surfaces, with a minimal amount of sink marks, wall transitions, and projections. Sharp corners should be broken to a minimum of 0.5 mm (0.020 in.). [959]

19 Polypropylene Data Collection

19.1 Data Sheet Properties

Material family					polypropylene homopolymer	polypropylene homopolymer, flame retardant	polypropylene homopolymer, fibers	polypropylene homopolymer, cast film	polypropylene, 10% talc	polypropylene, 20% talc	polypropylene, 20% talc, easy-flow
Supplier					BASF	Vestolen GMBH	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst
Material Trade Name					Novolen 1100L	Vestolen P 7006 S	Vestolen P 4000	Novolen 1127 N	Hostacom M1 U01	Hostacom M2 N01	Hostacom M2 U01
Source ID					756, CAMPUS	711, CAMPUS	711, CAMPUS	756, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS
Test Notes	Test condition	Test Specimen	Test Method	(Unit)							

PROCESSING PROPERTIES

melt volume rate (230°C, 2.16 kg)			ISO 1133, DIN 53735, CAMPUS	ml/10min	8	3	23	15	20	2.3	18
melt volume rate (190°C, 5 kg)			ISO 1133, CAMPUS	"	12			30	38	4.2	34
melt volume rate (230°C, 5 kg)		test specimen note: granules	DIN 53479	"					85	10	78
melt flow rate (230°C, 2.16 kg)			ISO 1133, DIN 53735	g/10min	5	2.4	17.5	11	16	2	16
melt flow rate (190°C, 5 kg)			"	"	9	4.5	33	22	28	3.8	28
melt flow rate (230°C, 5 kg)			"	"		11	80		67	9	67
molding shrinkage (parallel)		parallel to flow	ISO 2577, CAMPUS	%	1.3						
molding shrinkage (normal)		perpendicular to flow	"	"							
processing shrinkage				"							
molecular weight distribution			GPC								

MECHANICAL PROPERTIES

tensile modulus (secant, 1 mm/min)	test temperature: 21-25°C; relative humidity: 50%; strain rate: 1 mm/min; elongation: 0.05-0.25%; atmosphere according to ISO 291	ISO 3167 multi-purpose test specimen	ISO 527-1, ISO 527-2, CAMPUS, DIN 53457	MPa	1500	1500	1650		2300	2500	2600
stress at yield (50 mm/min)	test temperature: 21-25°C; relative humidity: 50%; strain rate: 50 mm/min; atmosphere according to ISO 291	"	ISO 527-1, ISO 527-2, CAMPUS, DIN 53455	"	35	34	35		35	32	32
strain at yield (50 mm/min)	"	"	"	%	10	8	8		6	6	5
strain at break (50 mm/min)	"	"	"	"	>50	>50	>50		8	20	3
tensile strength at break (5 mm/min)	test temperature: 21-25°C; relative humidity: 50%; strain rate: 5 mm/min; atmosphere according to ISO 291	"	"	MPa							
strain at break (5mm/min)	"	"	"	%							
shear modulus	test temperature: 21-25°C; relative humidity: 50%		ISO 537, DIN 53445	MPa	750	800	850				
tensile creep modulus (1 hour)	test temperature: 21-25°C; relative humidity: 50%; elongation: <=0.5%; atmosphere according to ISO 291	ISO 3167 multi-purpose test specimen	ISO 899-1, CAMPUS	"	700				1600	1650	
tensile creep modulus (1000 hour)	"	"	"	"	380				800	850	
Charpy impact strength (23°C)	test temperature: 23°C; relative humidity: 50%; atmosphere according to ISO 291	80 x 10 x 4 mm	ISO 179/1eU, CAMPUS	kJ/m2	140	no failure	80		50	50	45
Charpy impact strength (-30°C)	test temperature: -30°C	"	"	"	16	20	15				
Charpy notched impact strength (23°C)	test temperature: 23°C; relative humidity: 50%; atmosphere according to ISO 291	80 x 10 x 4 mm, V notch, r= 0.25 mm	ISO 179/1eA, CAMPUS	"	3	4.5	3		2.5	4	3.2
Charpy notched impact strength (-30°C)	test temperature: -30°C	"	"	"	1.5	2.2	1.7				
Izod impact strength (23°C)	test temperature: 23°C; relative humidity: 50%	80 x 10 x 4 mm	ISO 180/1C	"	65	90	60				
Izod impact strength (-30°C)	test temperature: -30°C	"	"	kJ/m2	13	15	15				
notched Izod impact strength (23°C)	test temperature: 23°C; relative humidity: 50%	80 x 10 x 4 mm	ISO 180/1A	kJ/m2	3.5	4	2.2				
notched Izod impact strength (-30°C)	test temperature: -30°C	"	"	"	1.3	2	1.6				
notched tensile impact strength	test temperature: 23°C; relative humidity: 50%; atmosphere according to ISO 291	80 x 10 x 4 mm, 45° double V notch, r= 1.0 mm recommended	ISO 8256, CAMPUS	"					35	40	35
impact strength	test temperature: 23°C; relative humidity: 50%	small size standard test bar	DIN 53453	"					33	38	25
notched impact strength	"	"	"	"					2.5	5	3
Ball indentation hardness	load: 358 N; note: H 358/30	>=10 x >=10 x 4 mm	ISO 2039T1, DIN 2039T1	MPa	70	75	78		95	81	90

polypropylene, 40% talc	polypropylene, 20% glass fiber	polypropylene, 20% chemi- cally coupled glass fibers	polypropylene, 30% chemi- cally coupled glass fibers	polypropylene block copolymer	polypropylene, block copoly- mer, UV stabilized	polypropylene random copolymer	polypropylene random copolymer	metallocene polypropylene	metallocene polypropylene	polypropylene, elastomer- modified	Polypropylene elastomer blend recyclate	Material family
Hoechst	Hoechst	Hoechst	Hoechst	Vestolen GMBH	BASF	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst	Hoechst	Supplier
Hostacom M4 N01	Hostacom G2 N01	Hostacom G2 U02	Hostacom G3 N01	Vestolen P 7700	Novolen 2660 M	Vestolen P 9421	Novolen 3240 NC	Hostacen XAV10A FOB	Hostacen XAW10A SAB	Hostalen PPN 8018A	Hostalen PP 3100	Material Trade Name
326, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS	711, CAMPUS	CAMPUS	711, 712, CAMPUS	756, CAMPUS	709	731	841, CAMPUS	CAMPUS	Source ID
												Test Notes

PROCESSING PROPERTIES

2.5	2	17	1	2.5	10	0.4	16	30	60		9	melt volume rate (230°C, 2.16 kg)
4.5	3.5	28	2				30			6		melt volume rate (190°C, 5 kg)
11	8.5	55	5							35		melt volume rate (230°C, 5 kg)
2.5	1.7	15	1	1.9		0.3	11					melt flow rate (230°C, 2.16 kg)
4.5	3.2	23	2	4.5		0.5	22					melt flow rate (190°C, 5 kg)
11	7.5	55	4.5	10		1.5				26		melt flow rate (230°C, 5 kg)
					1.3		1.3					molding shrinkage (parallel)
												molding shrinkage (normal)
							0.6-2.0					processing shrinkage
								2.5	2.5			molecular weight distribution

MECHANICAL PROPERTIES

3800	2900	4600	6500	1500	1150	900	1100	1350	1450	850	900	tensile modulus (secant, 1 mm/min)
33	33	70		30	21	25	28			20	18	stress at yield (50 mm/min)
4	8			8	6	12	12			10	7	strain at yield (50 mm/min)
6	15		3	>50	>50	>50	>50			>50	>50	strain at break (50 mm/min)
		75	85			40 (strain rate: 50 mm/min; ISO 527)						tensile strength at break (5 mm/min)
		4	3									strain at break (5mm/min)
				650		400	550					shear modulus
2400	2300	3400	4800	1200						550		tensile creep modulus (1 hour)
1200	1300	2400	3200	450						250		tensile creep modulus (1000 hour)
30	50	40	40	no failure	no failure	no failure	200			no failure	no failure	Charpy impact strength (23°C)
				70	170	50	15			190		Charpy impact strength (-30°C)
3	4.5	9	9	9	45	20	6			65	NB	Charpy notched impact strength (23°C)
				4.5	6	2.5	1.5			8	5.5	Charpy notched impact strength (-30°C)
				no failure		no failure	non-breakable					Izod impact strength (23°C)
				65		30	20					Izod impact strength (-30°C)
				7		20	6.5					notched Izod impact strength (23°C)
				4		2.5	1.5					notched Izod impact strength (-30°C)
40	40	36	50									notched tensile impact strength
18	50	24	22									impact strength
4	5	7	6									notched impact strength
85	80	105	110				62	70	70			Ball indentation hardness

Material family					polypropylene homopolymer	polypropylene homopolymer, flame retardant	polypropylene homopolymer, fibers	polypropylene homopolymer, cast film	polypropylene, 10% talc	polypropylene, 20% talc	polypropylene, 20% talc, easy-flow
Supplier					BASF	Vestolen GMBH	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst
Material Trade Name					Novolen 1100L	Vestolen P 7006 S	Vestolen P 4000	Novolen 1127 N	Hostacom M1 U01	Hostacom M2 N01	Hostacom M2 U01
Source ID					756, CAMPUS	711, CAMPUS	711, CAMPUS	756, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS
Test Notes	Test condition	Test Specimen	Test Method	(Unit)							

MECHANICAL PROPERTIES (Continued)

Ball indentation hardness	load: 132 N		ISO 2039T1	N/mm2							
flexural stress (3.5% strain)	test temperature: 23°C; relative humidity: 50%	80 x 10 x 4 mm, from injection molded sheet	DIN 53452	"		36	38		50 (specimen from compression molded sheet)	45	47
creep modulus (flexure, 1 min value)	stress: 12 MPa	120 x 20 x 6 mm, injection molded		"					2700	2500	3000
flexural modulus			ISO 178	MPa							

THERMAL PROPERTIES

melting temperature				°C	163 IDTA or DSC; 10°C/min; ISO 3146, CAMPUS)			163 IDTA or DSC; 10°C/min; ISO 3146, CAMPUS)			
crystalline melting range				"		164-168 (DIN 53736 B2)	164-168 (DIN 53736 B2)		164-167 (polarizing microscope; 20µm microtome section)	164 - 167 (polarizing microscope; 20µm microtome section)	164-167 (polarizing microscope; 20µm microtome section)
heat deflection temperature at 0.45 MPa		80 x 10 x 4 mm	ISO 75-1, ISO 75-2, CAMPUS	"	85	85	80		120 (injection molded specimen, 127 x 12.7 x 3.2 mm; DIN 53461, ISO 75)	120 (injection molded specimen, 127 x 12.7 x 3.2 mm; DIN 53461, ISO 75)	
heat deflection temperature at 1.8 MPa		"	"	"	55	55	55		60	70	70
heat deflection temperature at 5.0 MPa		injection molded, 127 x 12.7 x 3.2 mm	DIN 53461; ISO 75	"							
Vicat A softening temperature	load: 10N; note: 50°C/h	20 x 20 x 4 mm; from injection molded sheet	ISO/DIN 306, CAMPUS	"					153	153	153
Vicat B softening temperature	load: 50N; note: 50°C/h	>=10 x >=10 x 4 mm	ISO/DIN 306, CAMPUS	"	92	90	90		95	95	95
coefficient of linear thermal expansion (flow direction)	test temperature: 23-55°C	>=10 x >=10 x 4 mm	ASTM E831, CAMPUS	E-4/°C	1.35	1	1.5	1.35	1	1.0 (23-80°C; DIN 53752)	1
flammability UL94 at 1.6 mm		125 x 13 mm	UL 94, CAMPUS		HB	HB	HB		HB		
flammability UL94 at 1 mm			UL 94, CAMPUS			HB (at 0.8 mm)	HB (at 0.8 mm)		HB	HB	
oxygen index		80 x 10 x4 mm	ISO 4589, CAMPUS	%							
generic temperature index			UL 746B at 1 mm thickness	°C					65	65	
thermal conductivity	test temperature: 20°C	260 x 260 x 10 mm	DIN 52612 method A	W/(mK)	0.17				0.37	0.41 (8 mm sheet, injection molded)	0.41 (8 mm sheet, injection molded)
specific heat	"	granules	adiabatic calorimeter	KJ/(kg K)					1.57	1.52	1.49

ELECTRICAL PROPERTIES

relative permittivity at 50 Hz	test temperature: 21-25°C; relative humidity: 50%; atmosphere according to ISO 291	plate with dimensions 1.0 +/- 0.1 mm	IEC 250, CAMPUS, DIN 53483						2.4	2.8	2.8
relative permittivity at 100 Hz	"	"	IEC 250, CAMPUS	-	2.3	2.3	2.3		2.4	2.8	2.8
relative permittivity at 1 MHz	"	"	"	-	2.3			2.3	2.4	2.8	2.8
dissipation factor at 50 Hz (loss factor)		from 1 mm compression molded sheet	DIN 53483, VDE 0303 part 4	E-4					15	20	20
dissipation factor at 100 Hz (loss factor)	test temperature: 21-25°C; relative humidity: 50%; atmosphere according to ISO 291	plate with dimensions 1.0 +/- 0.1 mm	IEC 250, CAMPUS	E-4	0.7	30	5	0.7	15	20	20
dissipation factor at 1 MHz (loss factor)	"	"	"	E-4	2			2	10	10	10
volume resistivity	"	"	IEC 93, CAMPUS	Ohm*cm	>1E15	>1E15	>1E15	>1E15	1.00E+14	1.00E+14	>1E15
surface resistivity	"	"	"	Ohm	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14
dielectric strength	test temperature: 21-25°C; relative humidity: 50%; atmosphere according to ISO 291, short term test in transformer oil according to IEC 296	"	IEC 243-1, CAMPUS	kV/mm	140	30	40	140	40	40	43
dielectric constant at 50 Hz	frequency: 50 Hz		IEC 250								
comp. tracking index (CTI)	test temperature: 21-25°C; relative humidity: 50%; atmosphere according to ISO 291, test liquid A	>=15 x >=15 x 4 mm	IEC 112, CAMPUS	steps	600			600	600	600	600

polypropylene, 40% talc	polypropylene, 20% glass fiber	polypropylene, 20% chemi- cally coupled glass fibers	polypropylene, 30% chemi- cally coupled glass fibers	polypropylene block copolymer	polypropylene, block copoly- mer, UV stabilized	polypropylene random copolymer	polypropylene random copolymer	metallocene polypropylene	metallocene polypropylene	polypropylene, elastomer- modified	Polypropylene elastomer blend recyclate	Material family
Hoechst	Hoechst	Hoechst	Hoechst	Vestolen GMBH	BASF	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst	Hoechst	Supplier
Hostacom M4 N01	Hostacom G2 N01	Hostacom G2 U02	Hostacom G3 N01	Vestolen P 7700	Novolen 2660 M	Vestolen P 9421	Novolen 3240 NC	Hostacen XAV10A FOB	Hostacen XAW10A SAB	Hostalen PPN 8018A	Hostalen PP 3100	Material Trade Name
326, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS	711, CAMPUS	CAMPUS	711, 712, CAMPUS	756, CAMPUS	709	731	841, CAMPUS	CAMPUS	Source ID
												Test Notes

MECHANICAL PROPERTIES (CONTINUED)

				62		43				34		Ball indentation hardness
50	40	90	120	34		20						flexural stress (3.5% strain)
3300	2400	4300	5500									creep modulus (flexure, 1 min value)
								1200	1350			flexural modulus

THERMAL PROPERTIES

					163 (DTA or DSC; 10°C/min; ISO 3146, CAM- PUS)		149 (DTA or DSC; 10°C/min; ISO 3146, CAM- PUS)	150 (DSC)	150 (DSC)		167 (DTA or DSC; 10°C/min; ISO 3146, CAM- PUS)	melting temperature
164-167 (po- larizing micro- scope; 20µm microtome section)	164-167 (po- larizing micro- scope; 20µm microtome section)	164-167 (po- larizing micro- scope; 20µm microtome section)	164-167 (po- larizing micro- scope; 20µm microtome section)	160-164 (DIN 53736 B2)		150-154 (DIN 53736 B2)				164-167 (DIN 53736 B2)		crystalline melting range
125	120	150	155	90	80	65	70			70		heat deflection temperature at 0.45 MPa
75	75	130	140	55	50	45	48			50		heat deflection temperature at 1.8 MPa
52		92	100									heat deflection temperature at 5.0 MPa
153	150	160	160				130					Vicat A softening temperature
95	90	125	130	85	58	60	72			55	68	Vicat B softening temperature
0.8	0.8	0.9	0.7	1.5	1.5	1.5	1.85					coefficient of linear thermal expansion (flow direction)
			HB	HB		HB				HB		flammability UL94 at 1.6 mm
HB		HB	HB	HB (at 0.8 mm)		HB (at 0.8 mm)						flammability UL94 at 1 mm
												oxygen index
65			65									generic temperature index
0.56 (8 mm sheet, injection molded)	0.25 (8 mm sheet, injection molded)		0.30 (8 mm sheet, injection molded)			0.24	0.17					thermal conductivity
1.39	1.53	1.48	1.41			2				1.7		specific heat

ELECTRICAL PROPERTIES

2.9	2.8	2.8	3									relative permittivity at 50 Hz
2.9	2.8	2.8	3	2.3		2.3						relative permittivity at 100 Hz
2.5	2.4	2.4	2.6		2.3		2.3					relative permittivity at 1 MHz
50	10	10	10							2.5 (IEC 250)		dissipation factor at 50 Hz (loss factor)
50	10	10	10	5	0.7	5	0.7					dissipation factor at 100 Hz (loss factor)
20					2		2			3.5		dissipation factor at 1 MHz (loss factor)
>1E15	1.00E+14	1.00E+14	1.00E+14	>1E15	>1E15	>1E15	>E15			>E15		volume resistivity
1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14	1.00E+14			6.00E+11		surface resistivity
40	41	42	40	40	140	35	140					dielectric strength
										2.3		dielectric constant at 50 Hz
600	600	600	600		600		600			600		comp. tracking index (CTI)

Material family					polypropylene homopolymer	polypropylene homopolymer, flame retardant	polypropylene homopolymer, fibers	polypropylene homopolymer, cast film	polypropylene, 10% talc	polypropylene, 20% talc	polypropylene, 20% talc, easy-flow
Supplier					BASF	Vestolen GMBH	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst
Material Trade Name					Novolen 1100L	Vestolen P 7006 S	Vestolen P 4000	Novolen 1127 N	Hostacom M1 U01	Hostacom M2 N01	Hostacom M2 U01
Source ID					756, CAMPUS	711, CAMPUS	711, CAMPUS	756, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS
Test Notes	Test condition	Test Specimen	Test Method	(Unit)							

OTHER PROPERTIES

water absorption at saturation	test temperature: 21-25°C; relative humidity: 50%	50 x 50 x 1 mm	ISO 62, CAMPUS	%	0.1	0.8	0.8	0.1	2	2	2
water absorption at 24 hours	test temperature: 20°C	50 x 50 x 4 mm, from injection molded sheet	DIN 53495	mg					<2	<2	<2
water absorption at 96 hours	"	"	"	mg					<2	<2	<2
moisture absorption at saturation	test temperature: 21-25°C; relative humidity: 50%	50 x 50 x 1 mm	ISO 62, CAMPUS	%	0.1			0.1			
Density	test temperature: 21-25°C	>=10 x >=10 x 4 mm	ISO 1183, CAMPUS	g/m^3	0.91	0.943	0.902	0.91	0.97	1.05	1.04

MATERIAL SPECIFIC PROPERTIES

viscosity coefficient			ISO 1628, CAMPUS	cm^3/g		270	180		185	255	125
Isotaxy index				-		95	95				

MATERIAL CHARACTERISTICS

processing					injection molding, tape manufacture, monofilament extrusion	injection molding	other extrusion	film extrusion	injection molding	injection molding, other extrusion	injection molding
delivery Form					pellets	pellets	pellets	pellets	pellets	pellets	pellets
additives					unfilled	flame retarding agent, unfilled	unfilled	lubricants, anti-blocking agent	filled	filled	filled
features					platable	flame retardant, heat stabilized or stable to heat			heat stabilized or stable to heat	heat stabilized or stable to heat	heat stabilized or stable to heat
natural color		thickness: 2 mm	visual						translucent	translucent	translucent

PROCESSING DATA - INJECTION MOLDING

melt temperature				°C			220-250				
mold temperature				"			15-30				
injection pressure				bar			600-800				
back pressure				"			300-600				

PROCESSING DATA - PROFILE EXTRUSION

melt temperature											
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polypropylene, 40% talc	polypropylene, 20% glass fiber	polypropylene, 20% chemically coupled glass fibers	polypropylene, 30% chemically coupled glass fibers	polypropylene block copolymer	polypropylene, block copolymer, UV stabilized	polypropylene random copolymer	polypropylene random copolymer	metallocene polypropylene	metallocene polypropylene	polypropylene, elastomer-modified	Polypropylene elastomer blend recycle	Material family
Hoechst	Hoechst	Hoechst	Hoechst	Vestolen GMBH	BASF	Vestolen GMBH	BASF	Hoechst	Hoechst	Hoechst	Hoechst	Supplier
Hostacom M4 N01	Hostacom G2 N01	Hostacom G2 U02	Hostacom G3 N01	Vestolen P 7700	Novolen 2660 M	Vestolen P 9421	Novolen 3240 NC	Hostacen XAV10A FOB	Hostacen XAW10A SAB	Hostalen PPN 8018A	Hostalen PP 3100	Material Trade Name
326, CAMPUS	326, CAMPUS	326, CAMPUS	326, CAMPUS	711, CAMPUS	CAMPUS	711, 712, CAMPUS	756, CAMPUS	709	731	source id 841, CAMPUS	CAMPUS	Source ID
												Test Notes

OTHER PROPERTIES

2	2	2	2	0.8	0.1	0.8	0.1			0.1		water absorption at saturation
<2	<2	<2	<2									water absorption at 24 hours
<2	<2	<2	<2									water absorption at 96 hours
					0.1		0.1			0.1		moisture absorption at saturation
1.21	1.04	1.05	1.14	0.908	0.91	0.898	0.91	0.90	0.90	0.9	0.905	density

MATERIAL SPECIFIC PROPERTIES

185	230	110	170	400		450				260		viscosity coefficient
				95		85						Isotaxy index

MATERIAL CHARACTERISTICS

injection molding	injection molding, other extrusion	injection molding	injection molding	injection molding	injection molding	injection molding, other extrusion	injection molding	fiber extrusion	injection molding	injection molding	injection molding	processing
pellets	pellets	pellets	pellets	pellets	pellets	pellets	pellets	pellets	pellets	pellets	Pellets	delivery Form
filled	filled	filled	filled	unfilled	unfilled	unfilled	unfilled, nucleation		antistatic, nucleation	unfilled	Unfilled	additives
heat stabilized or stable to heat	heat stabilized or stable to heat	heat stabilized or stable to heat	heat stabilized or stable to heat	high impact or impact modified	high impact or impact modified, light stabilized or stable to light, UV stabilized or stable to light	heat stabilized or stable to heat	platable			high impact or impact modified	heat stabilized or stable to heat	features
translucent	white/opaque	white/opaque	white/opaque				transparent, platable					natural color

PROCESSING DATA - INJECTION MOLDING

				250-280								melt temperature
				25-50								mold temperature
				600-800								injection pressure
				300-600								back pressure

PROCESSING DATA - PROFILE EXTRUSION

						190-220						melt temperature
--	--	--	--	--	--	---------	--	--	--	--	--	------------------

19.2 Film Properties

Table 19.1 Film Properties of Coated and Uncoated Oriented Polypropylene Film

Material Family	POLYPROPYLENE	
Product Form	FILM	
Features	oriented	oriented; PVDC coated
Reference Number	268	268

MATERIAL CHARACTERISTICS

Sample Thickness	0.02 mm	0.022 mm
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TEST CONDITIONS

Temperature (°C)	20	20
Relative Humidity (%)	65	65

PHYSICAL PROPERTIES

Water Absorption - 24 hours (%)	0.3 {30°C }	0.3 {30°C }
Equilibrium Moist. Absorption (%)	0.2	0.2

MECHANICAL PROPERTIES

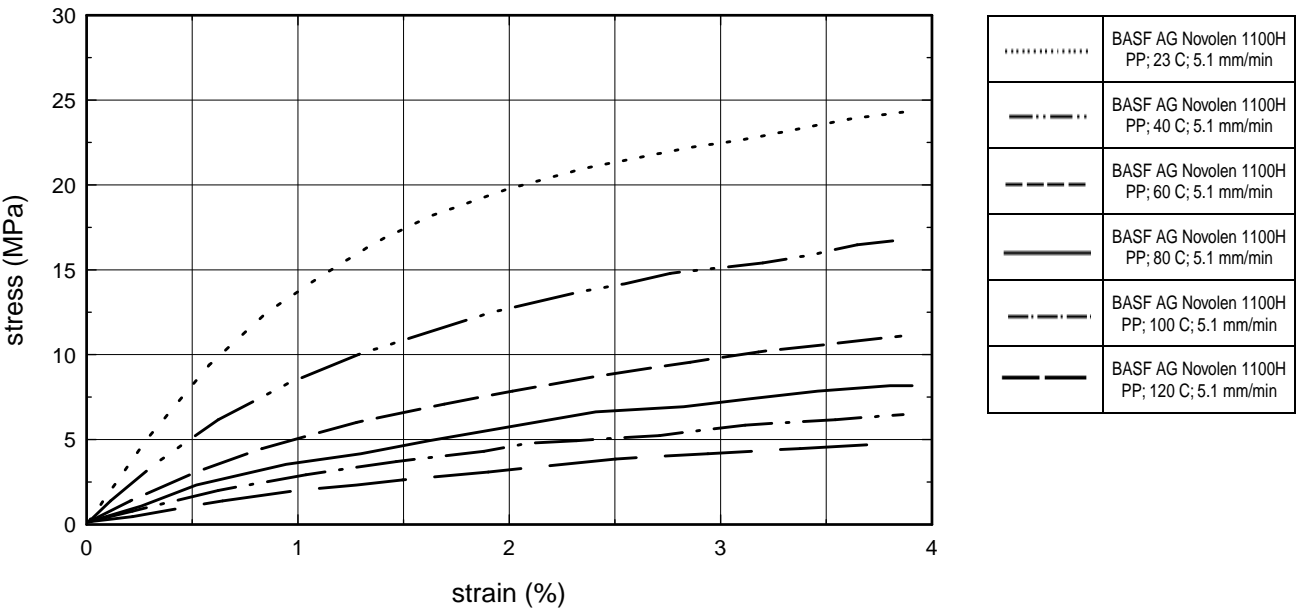
Modulus Of Elasticity - MD (MPa)	1860 {ASTM D882}	2157 {ASTM D882}
Modulus Of Elasticity - TD (MPa)	3431 {ASTM D882}	2549 {ASTM D882}
Tensile Strength @ Break - MD (MPa)	127.6 {ASTM D882}	137.2 {ASTM D882}
Tensile Strength @ Break - TD (MPa)	245.5 {ASTM D882}	215.8 {ASTM D882}
Ultimate Elongation - MD (%)	140 {ASTM D882}	140 {ASTM D882}
Ultimate Elongation - TD (%)	50 {ASTM D882}	60 {ASTM D882}
Impact Strength (kg-cm)	9	9
Burst Strength (MPa)	0.39 {JIS P8112}	0.39 {JIS P8112}
Pinhole Strength (g)	690 {JAS}	790 {JAS}
Elmendorf Tear Resistance - MD (g/mm)	200 {JIS P8116}	300 {JIS P8116}
Elmendorf Tear Resistance - TD (g/mm)	100 {JIS P8116}	200 {JIS P8116}
Tear Resistance - MD (g)	260	300
Tear Resistance - TD (g)	220	200

OTHER PROPERTIES

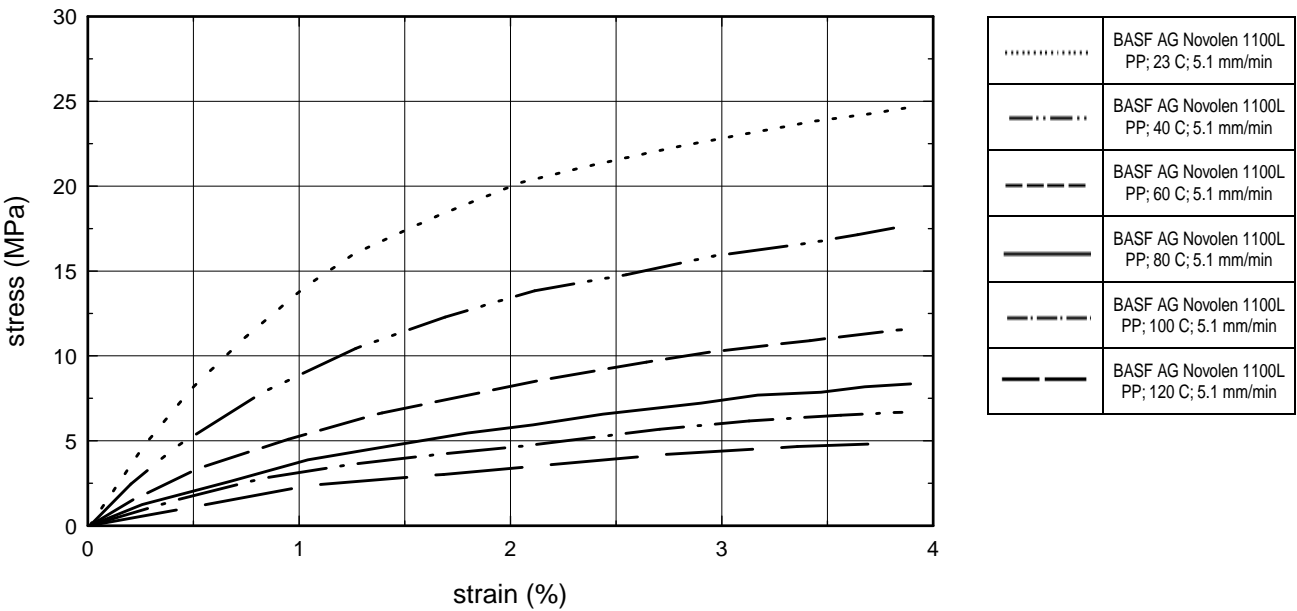
Melting Point (°C)	165	165
Haze (%)	2.2	3.5
Gloss		90
Surface Resistivity (ohms)	3.0×10^{15}	4.2×10^{15}
Slip Factor (°)	31	25
Dimensional Stability - MD (%)	-13.0	-10.4
Dimensional Stability - TD (%)	-15.0	-12.5

19.3 Stress vs. Strain Curves

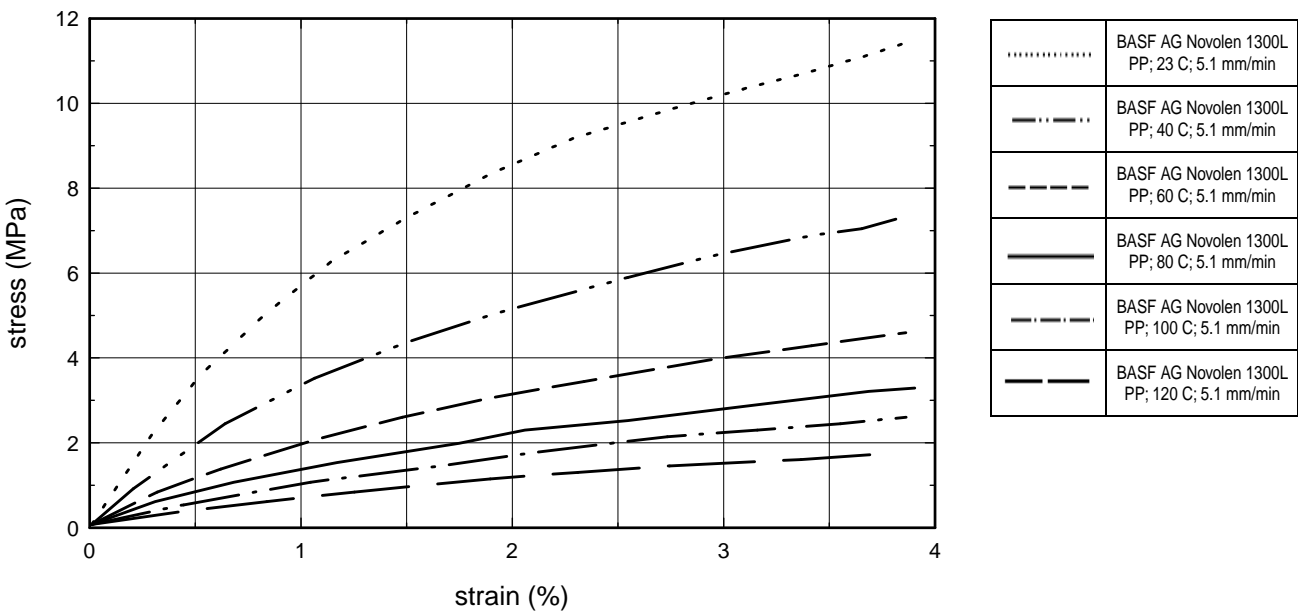
Graph 19.1 Stress vs. strain in tension for BASF AG Novolen 1100H polypropylene (melt volume index: 2.5 cc/ 10 min @ 230°C/ 2.16 kg, 4 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.



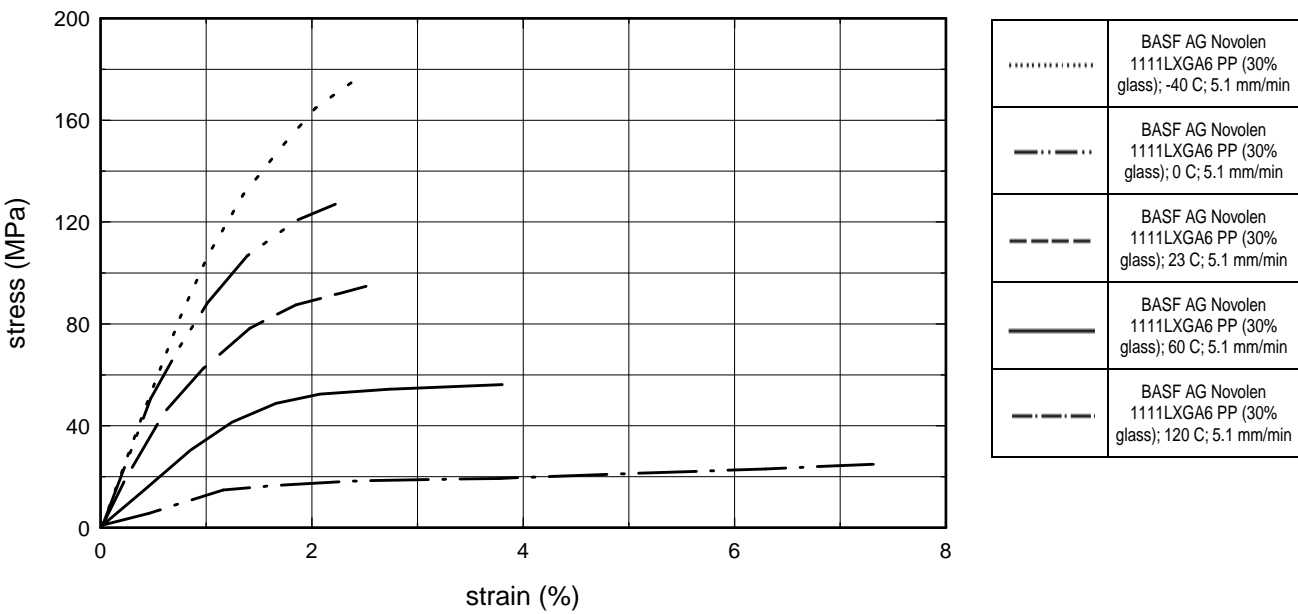
Graph 19.2 Stress vs. strain in tension for BASF AG Novolen 1100L polypropylene (melt volume index: 7 cc/ 10 min @ 230°C/ 2.16 kg, 13 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.



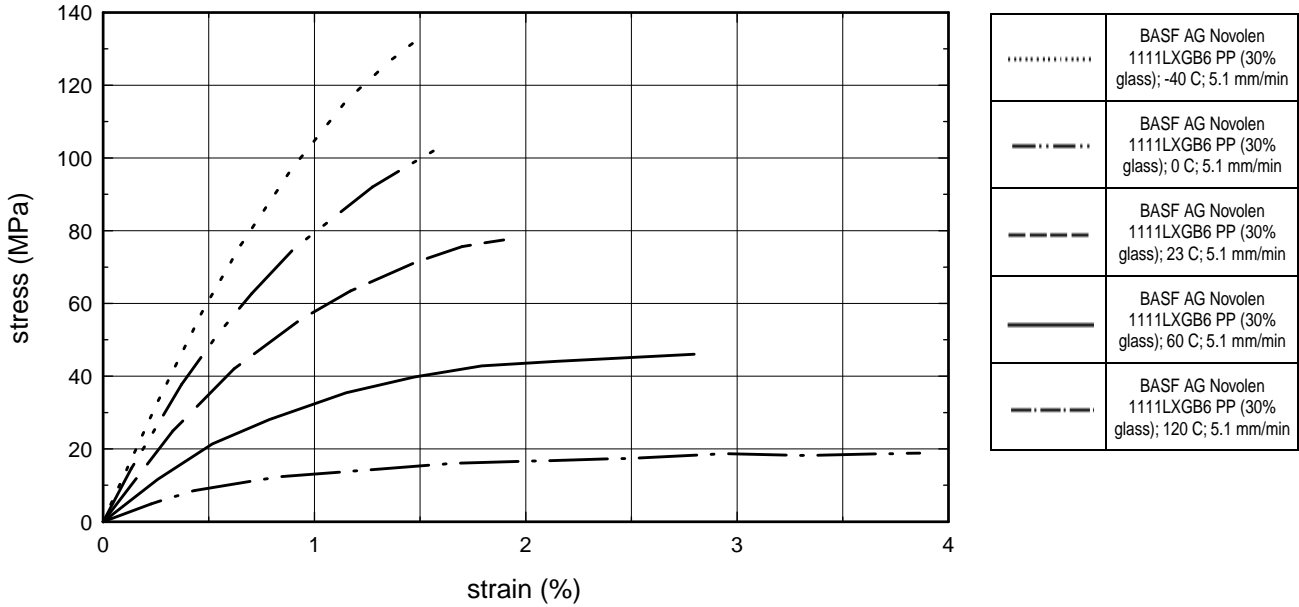
Graph 19.3 Stress vs. strain in tension for BASF AG Novolen 1300L polypropylene (melt volume index: 7 cc/ 10 min @ 230°C/ 2.16 kg, 10 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.



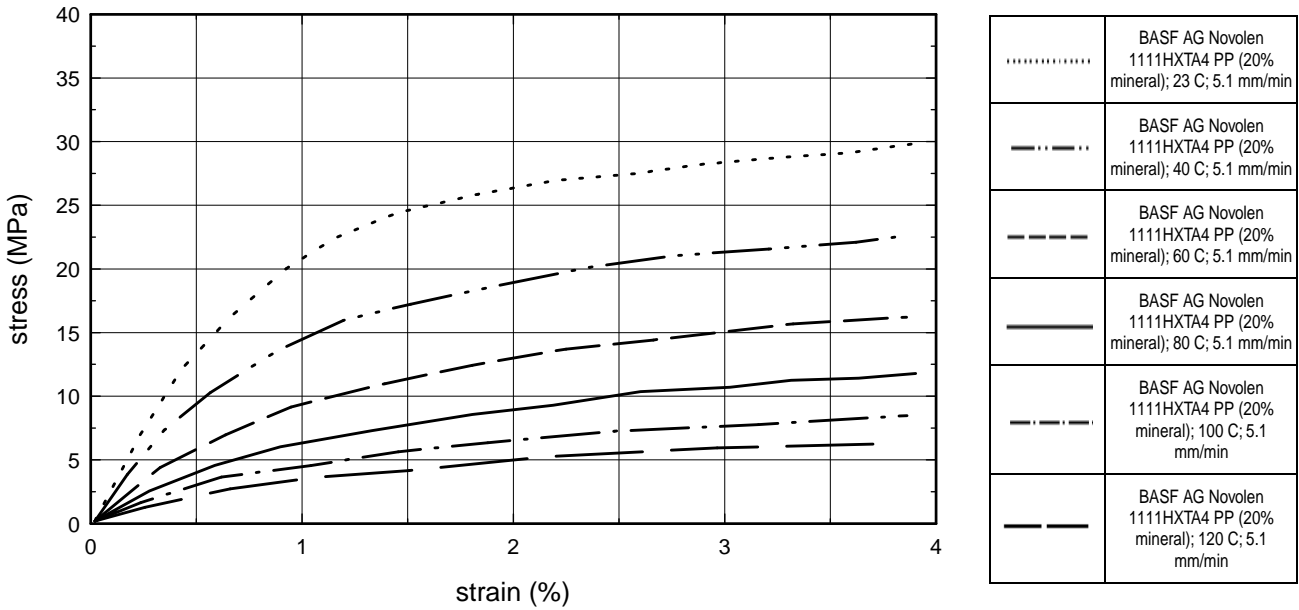
Graph 19.4 Stress vs. strain in tension for BASF AG Novolen 1111LXGA6 PP (30% glass; melt volume index: 2.4 cc/ 10 min @ 230°C/ 2.16 kg, 5.4 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.



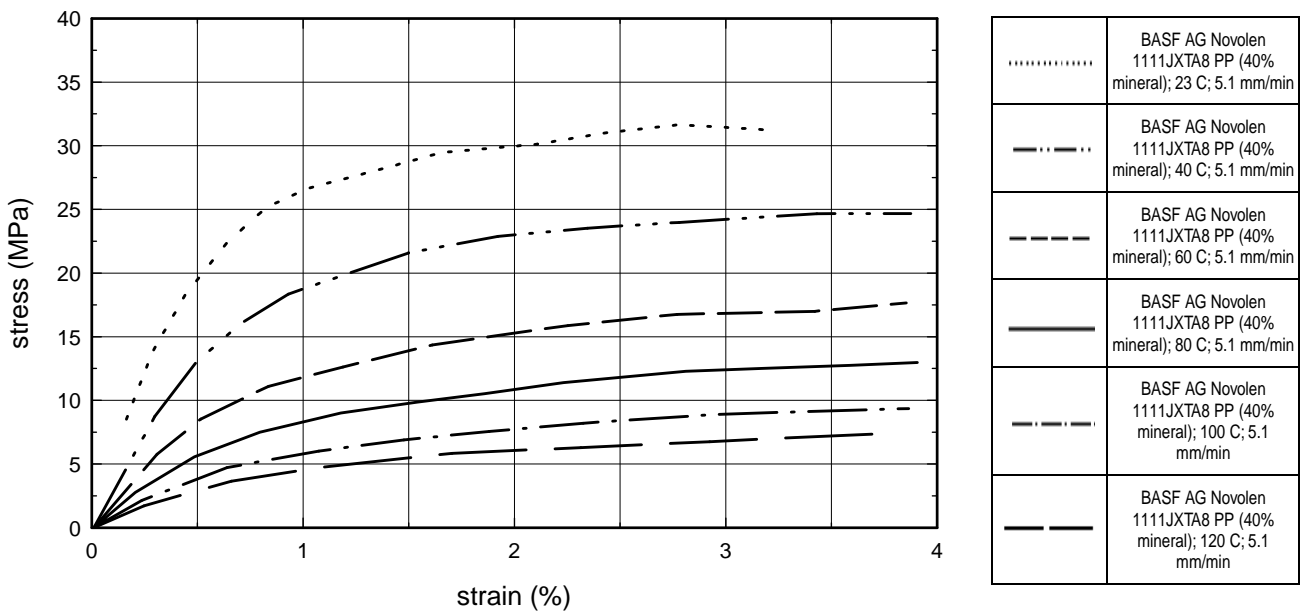
Graph 19.5 Stress vs. strain in tension for BASF AG Novolen 1111LXGB6 polypropylene (30% glass; melt volume index: 1.6 cc/ 10 min @ 230°C/ 2.16 kg, 5.2 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.



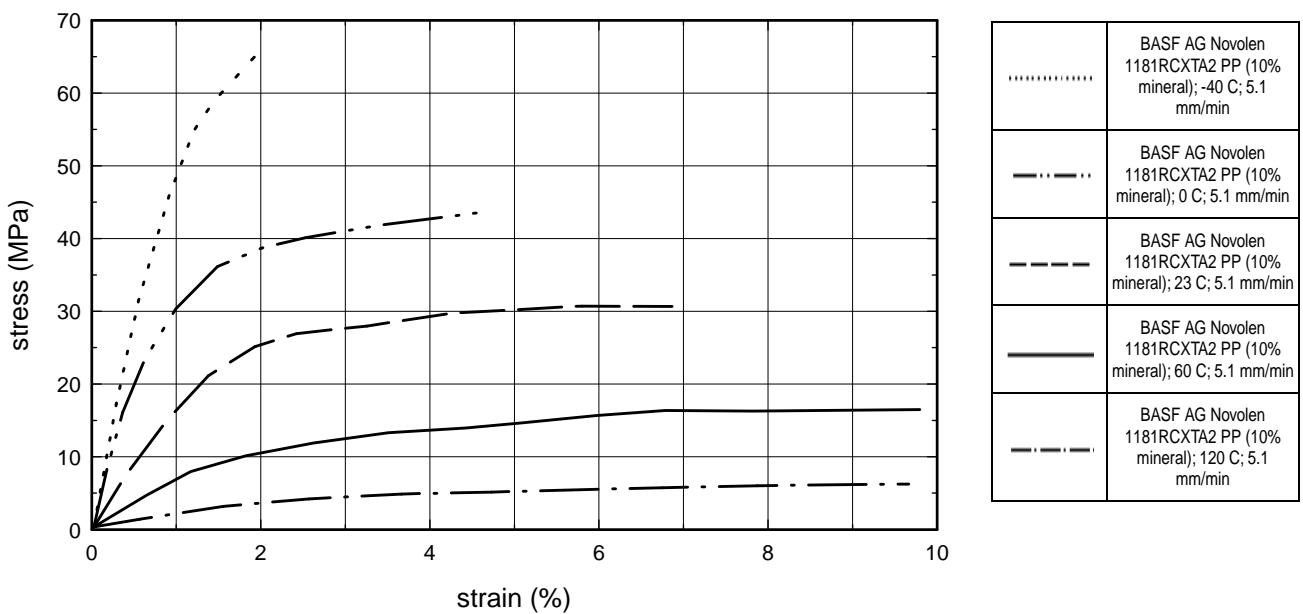
Graph 19.6 Stress vs. strain in tension for BASF AG Novolen 1111HXTA4 polypropylene (20% mineral; melt flow rate: 5 g/10 min.). Tested according to DIN 53455 at a strain rate of 5 mm/min.



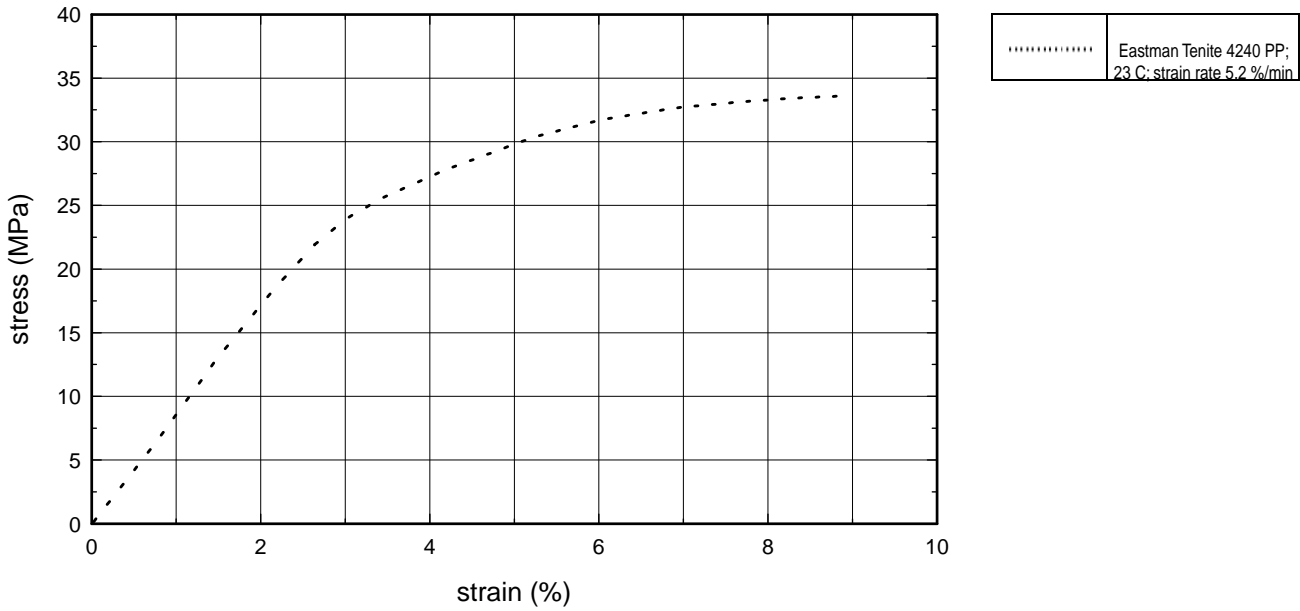
Graph 19.7 Stress vs. strain in tension for BASF AG Novolen 1111JXTA8 polypropylene (40% mineral; melt flow rate: 5 g/10 min.). Tested according to DIN 53455 at a strain rate of 5 mm/min.



Graph 19.8 Stress vs. strain in tension for BASF AG Novolen 1181RCXTA2 polypropylene (10% mineral; melt volume index: 28 cc/ 10 min @ 230°C/ 2.16 kg, 52 cc/ 10 min @ 190°C/ 5 kg). Tested according to DIN 53455 at a strain rate of 5 mm/min.

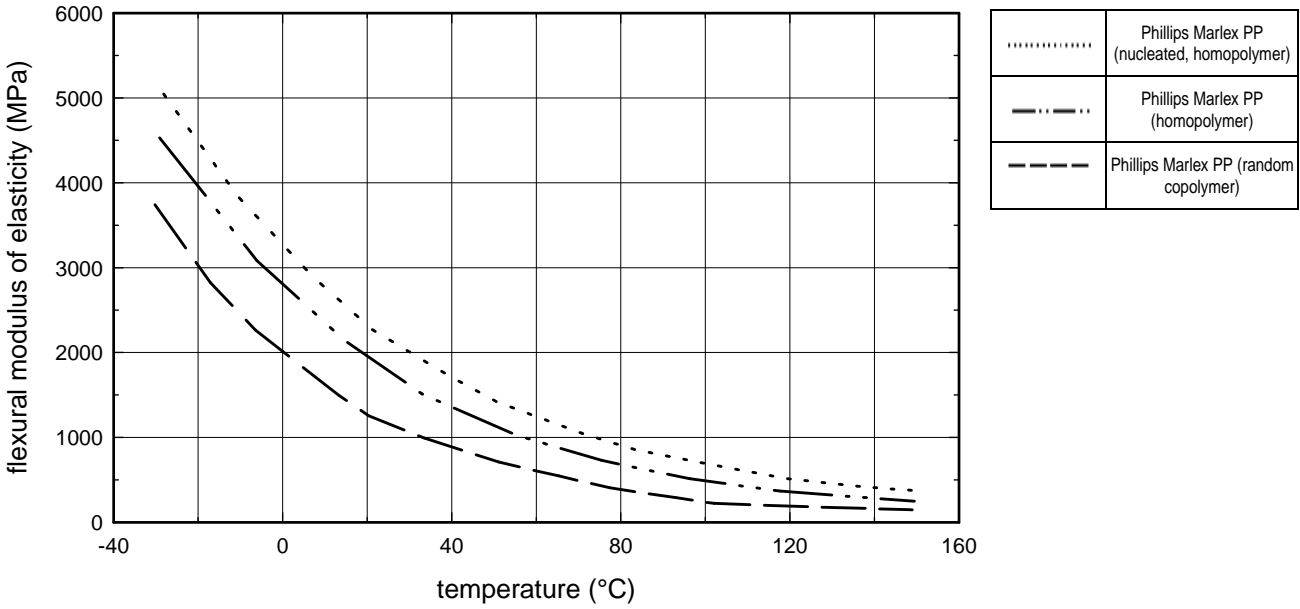


Graph 19.9 Stress vs. strain in tension for Eastman Tenite 4240 polypropylene (melt flow rate: 10 g/ 10min.). Tested at a strain rate of 5.2 %/min.

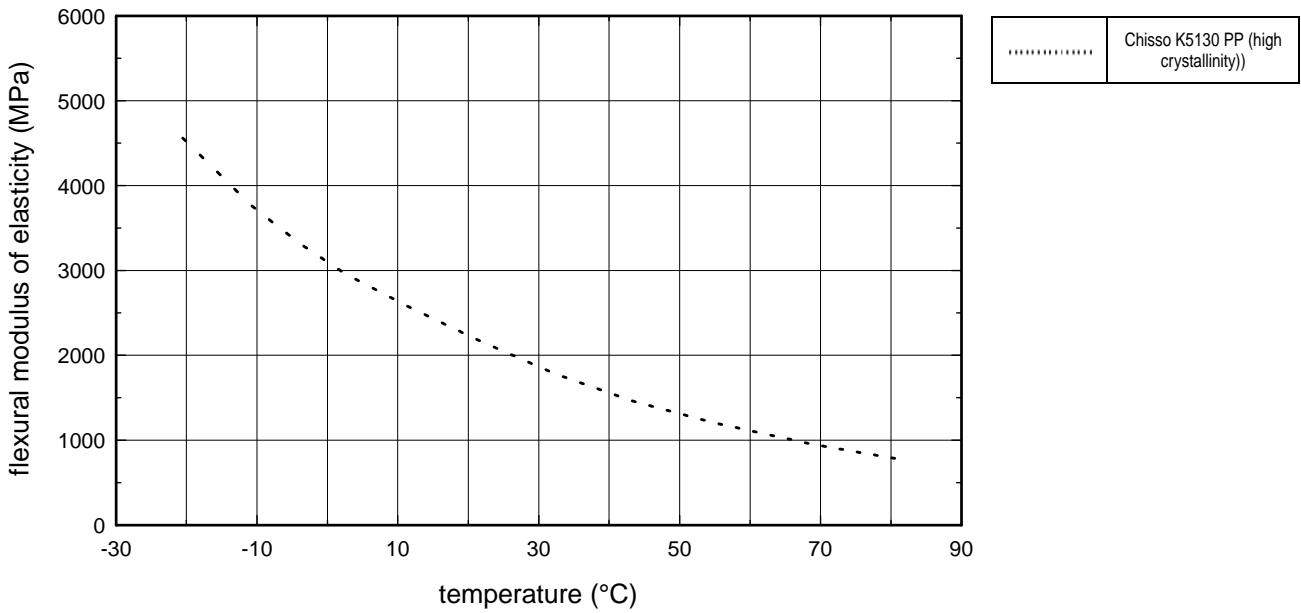


19.4 Temperature-Mechanical Property Relationship

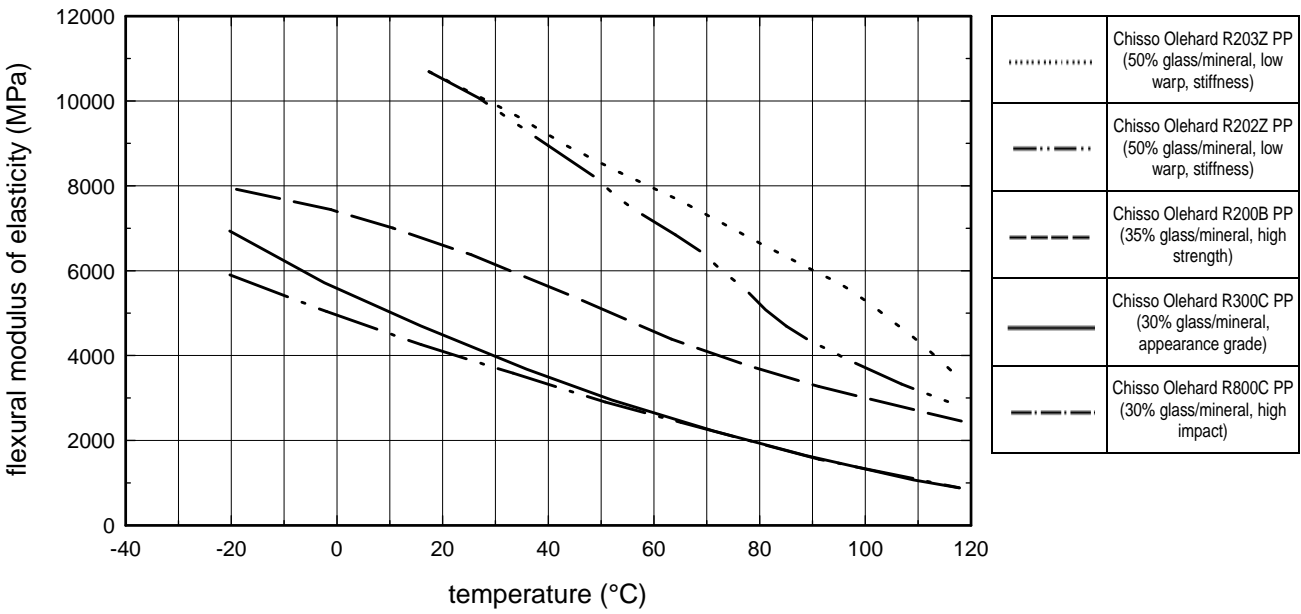
Graph 19.10 Flexural modulus of elasticity vs. temperature for Phillips Marlex polypropylene.



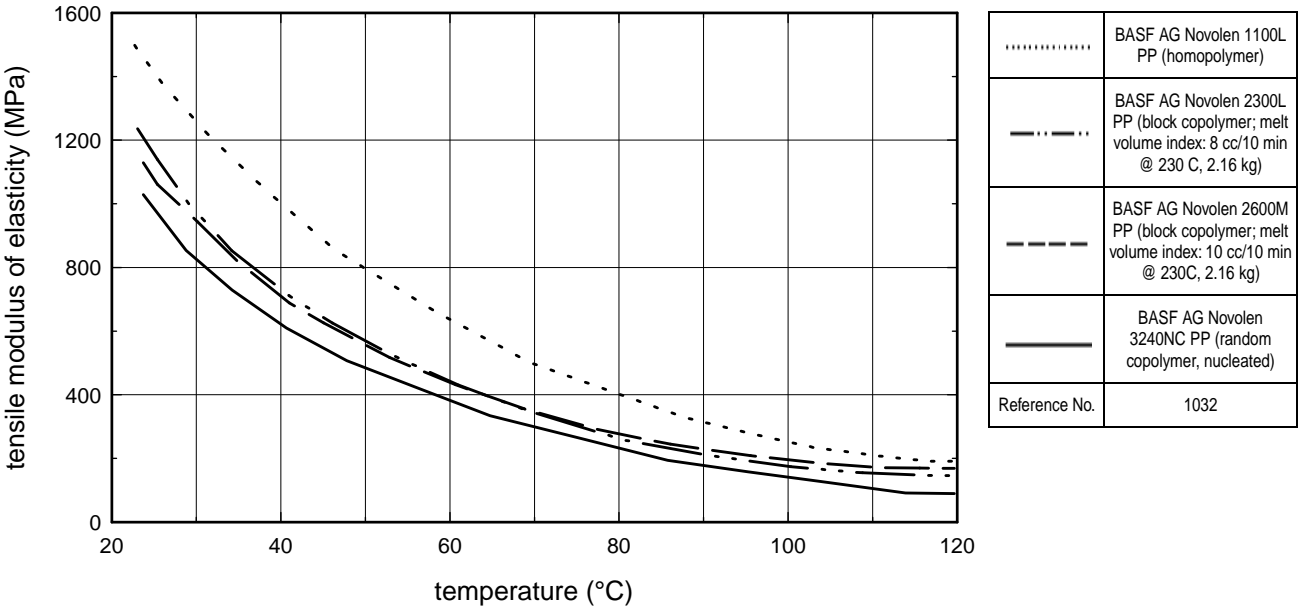
Graph 19.11 Flexural modulus of elasticity vs. temperature for Chisso high crystallinity polypropylene.



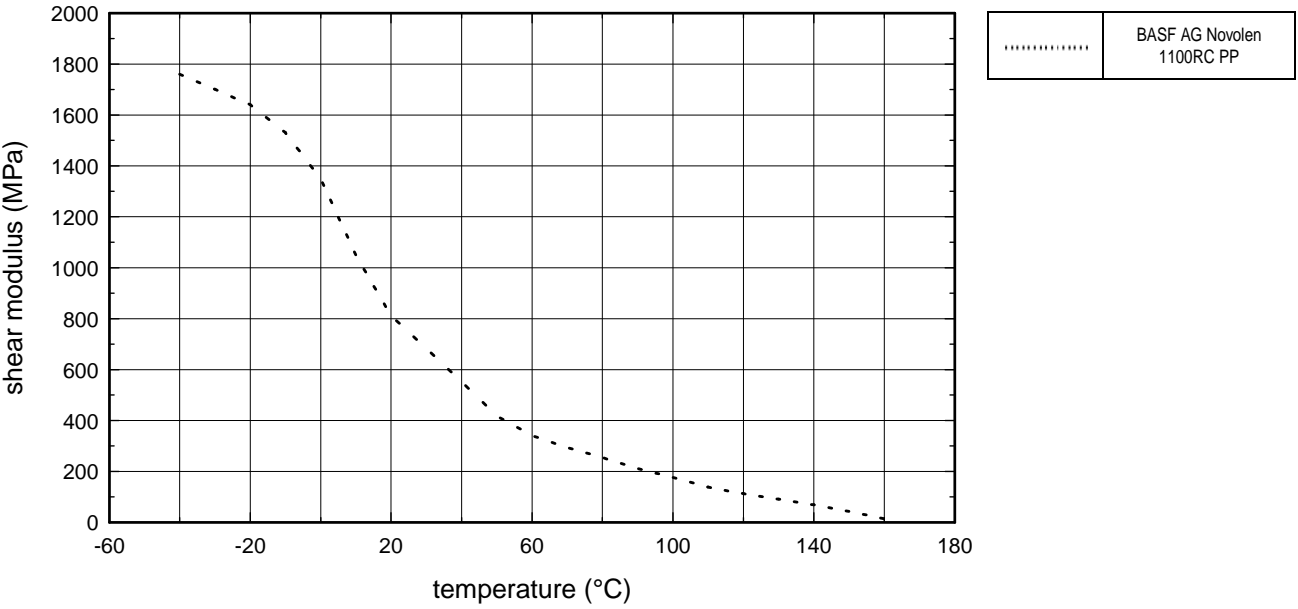
Graph 19.12 Flexural modulus of elasticity vs. temperature for Chisso Olehard glass/ mineral filled polypropylene.



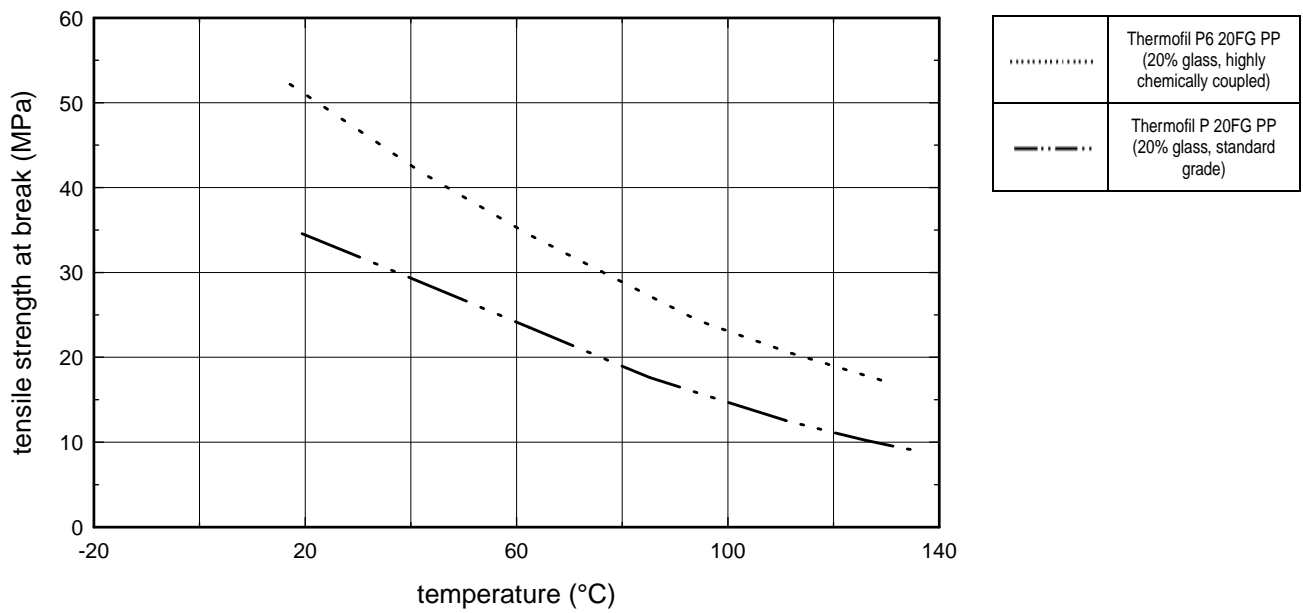
Graph 19.13 Tensile modulus of elasticity vs. temperature for BASF AG Novolen polypropylene.



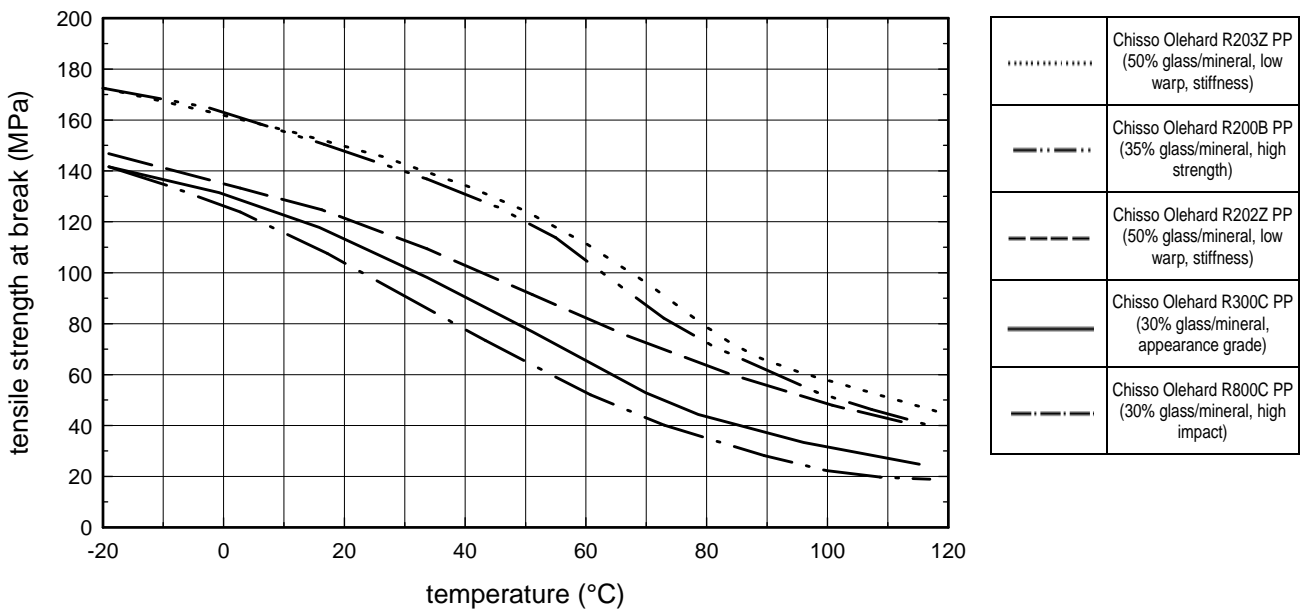
Graph 19.14 Shear modulus vs. temperature for BASF AG Novolen 1100RC polypropylene homopolymer.



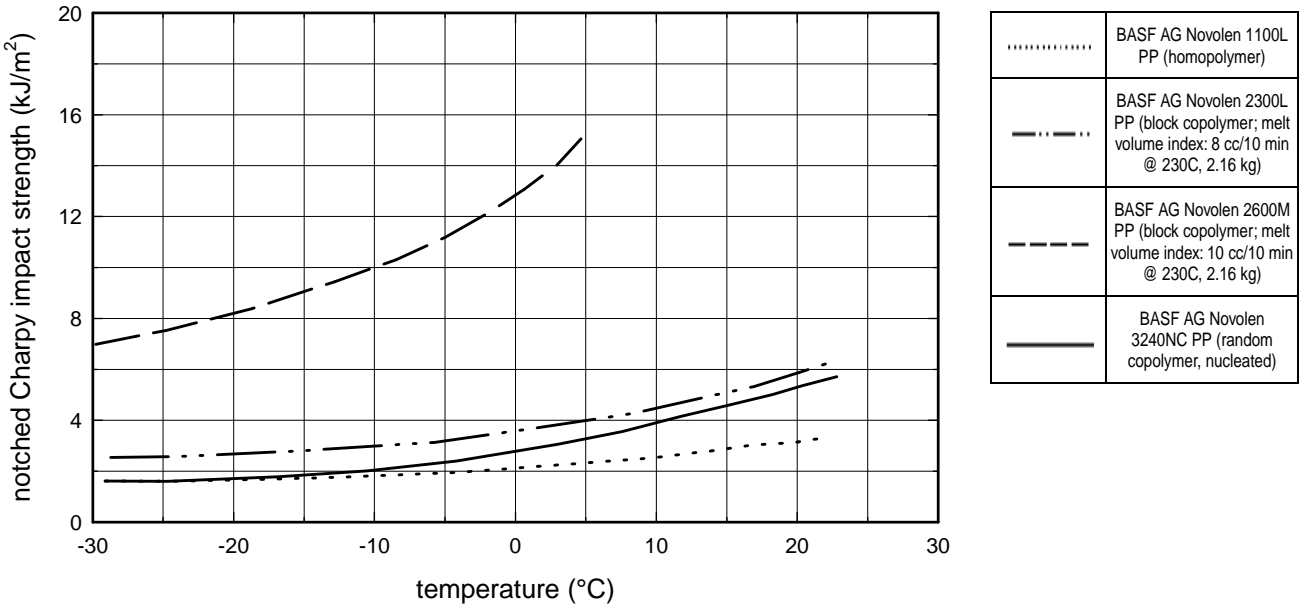
Graph 19.15 Tensile strength at break vs temperature for 20% glass fiber Thermofil Polypropylene.



Graph 19.16 Tensile strength at break vs temperature for glass fiber/ mineral filled Chisso Olehard Polypropylene.

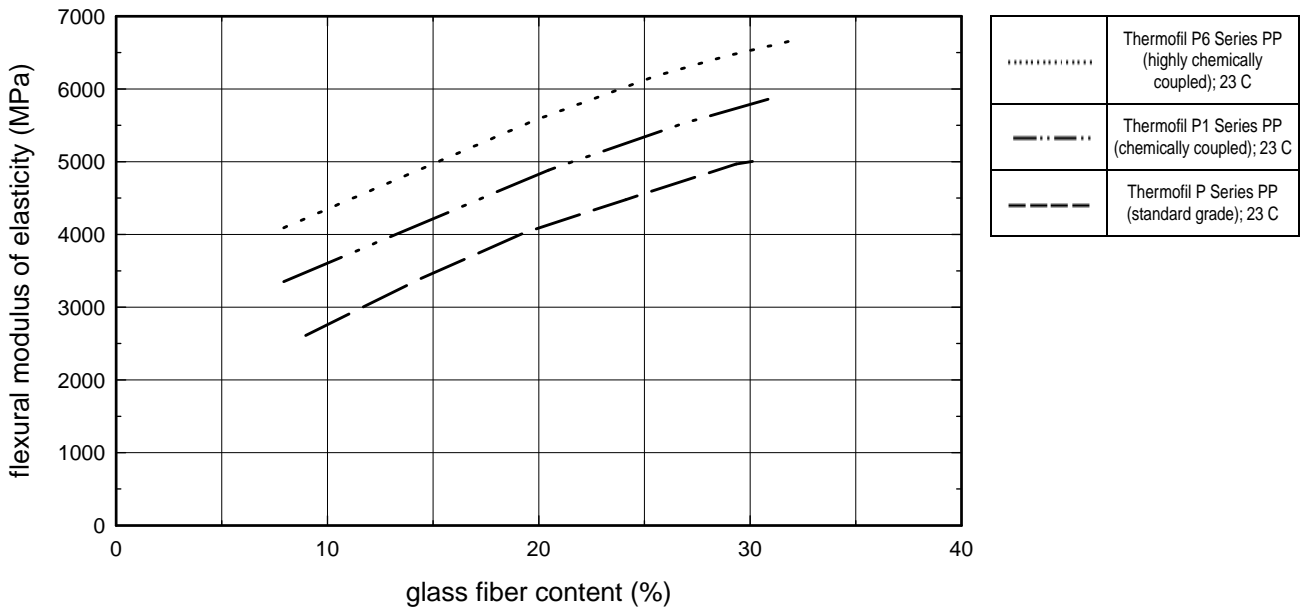


Graph 19.17 Notched Charpy impact strength vs. temperature for BASF AG Novolen polypropylene.

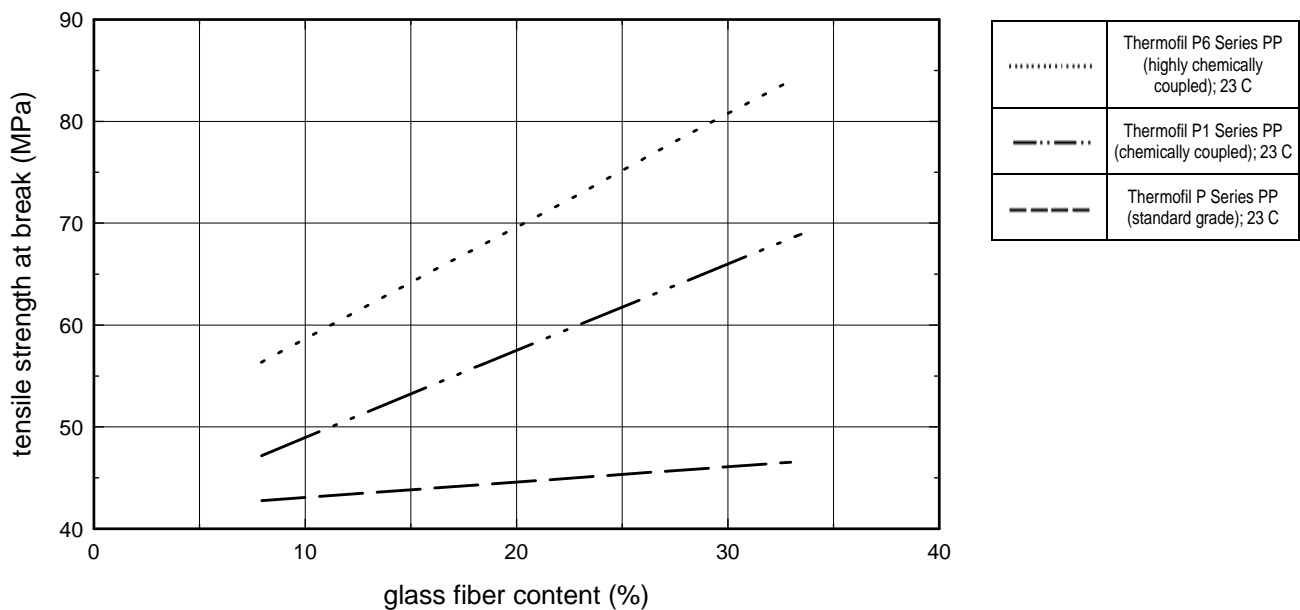


19.5 Composition-Mechanical Property Relationship

Graph 19.18 Flexural modulus of elasticity vs glass fiber content for Thermofil Polypropylene.

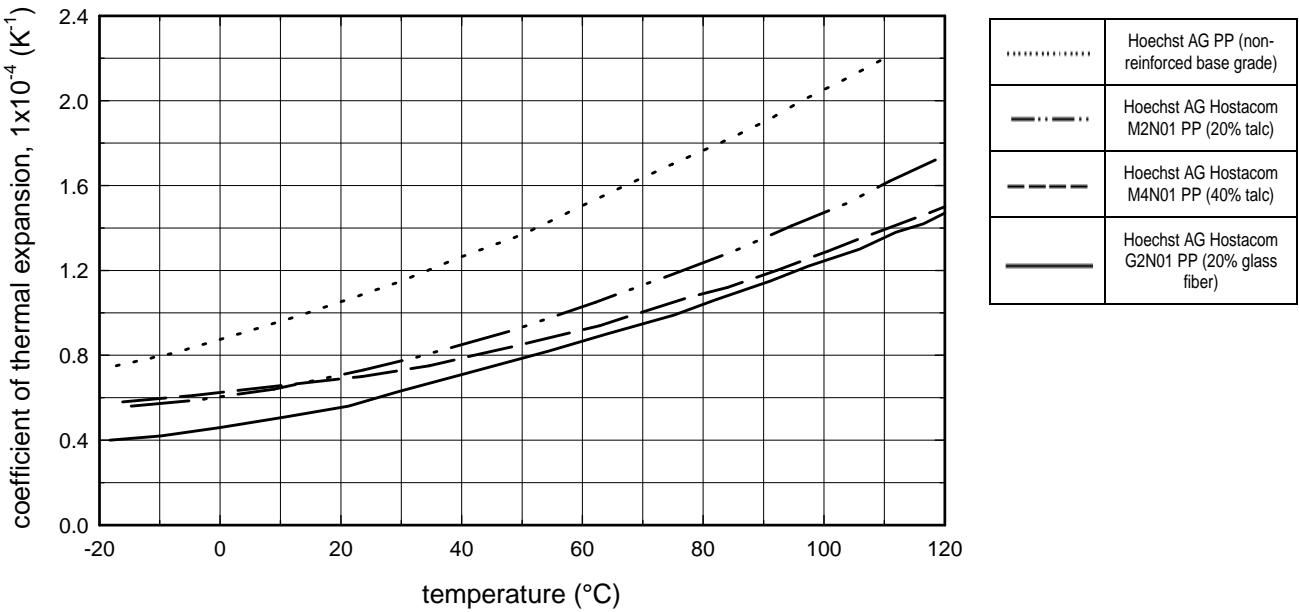


Graph 19.19 Tensile strength at break vs glass fiber content for Thermofil polypropylene.

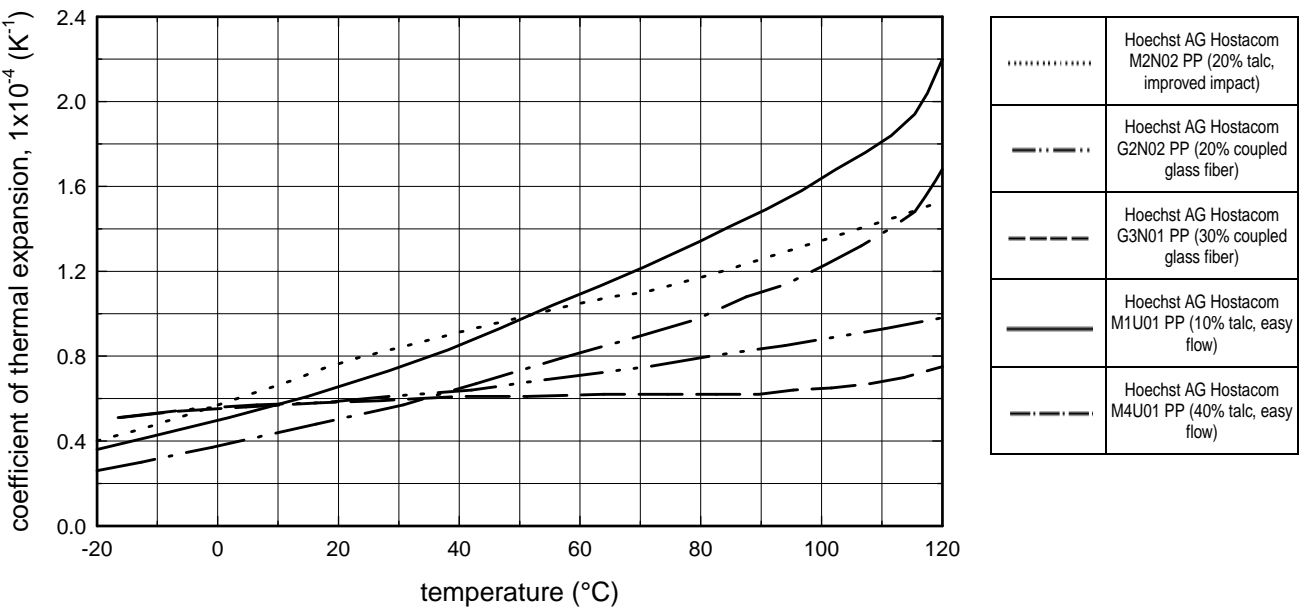


19.6 Temperature-Thermal Property Relationship

Graph 19.20 Coefficient of thermal expansion vs. temperature for Hoechst AG Hostacom polypropylene. Measured in flow direction.

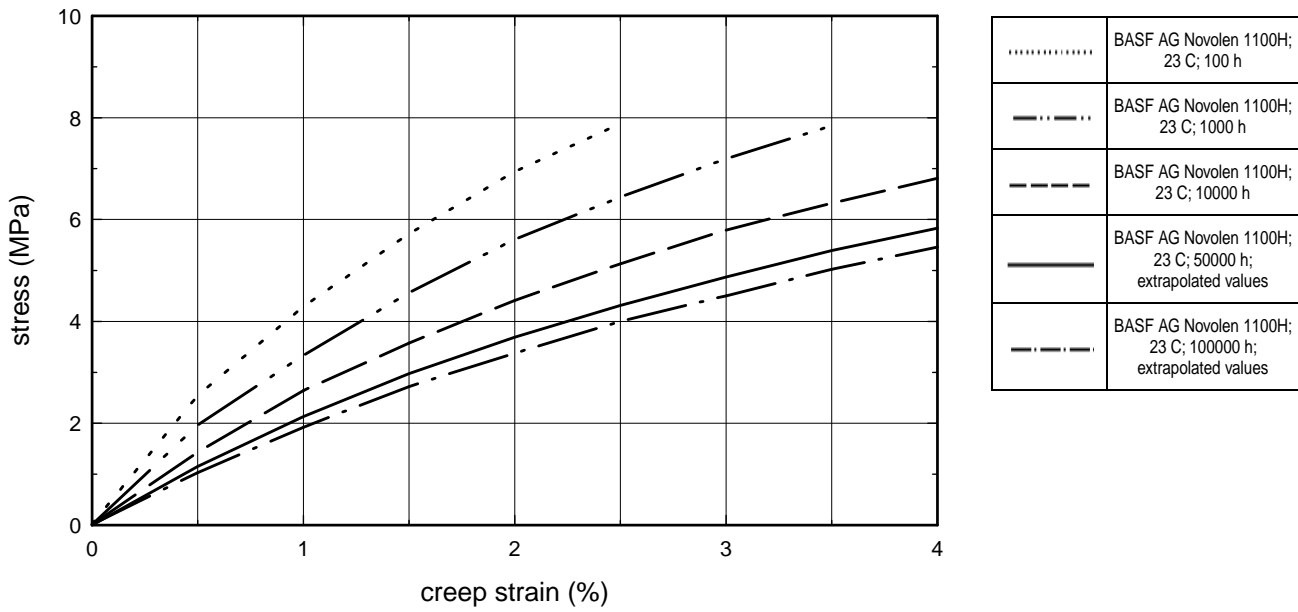


Graph 19.21 Coefficient of thermal expansion vs. temperature for Hoechst AG Hostacom polypropylene. Measured in flow direction.

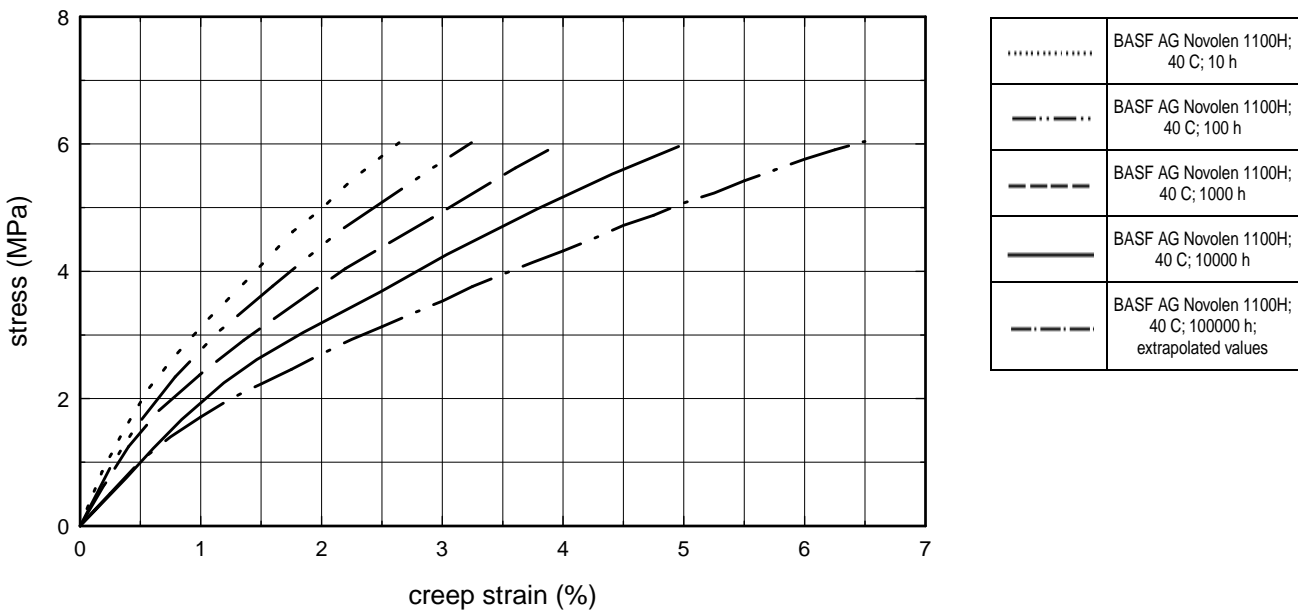


19.7 Creep and Stress Relaxation

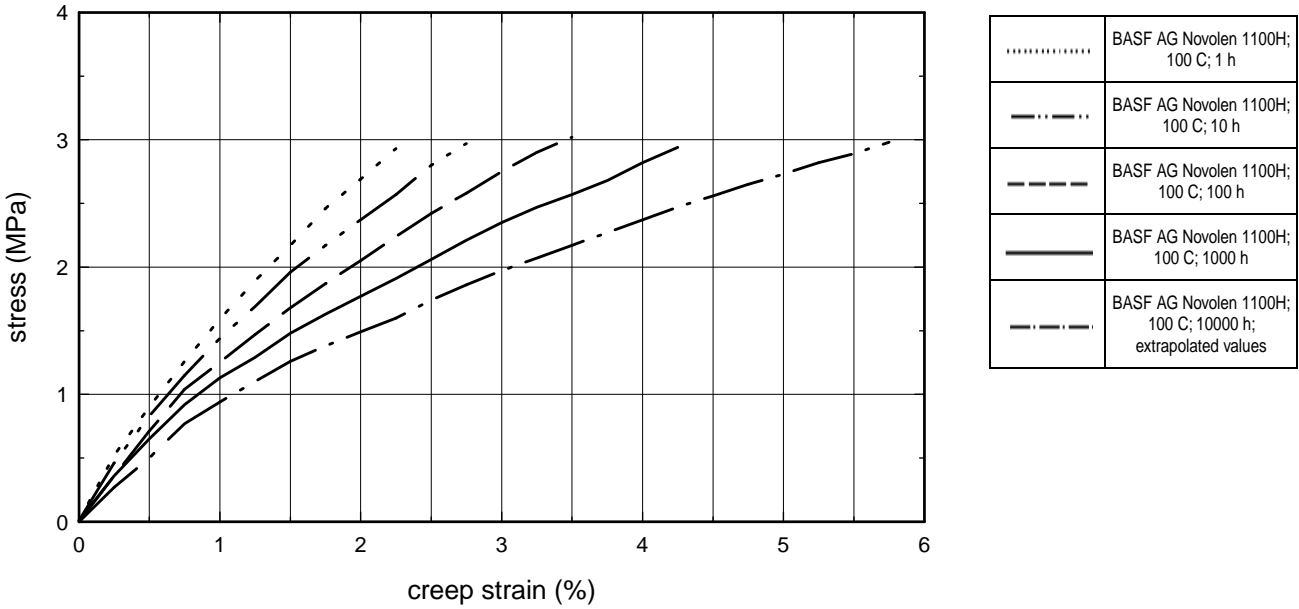
Graph 19.22 Isochronous stress vs. strain in tension @ 23°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



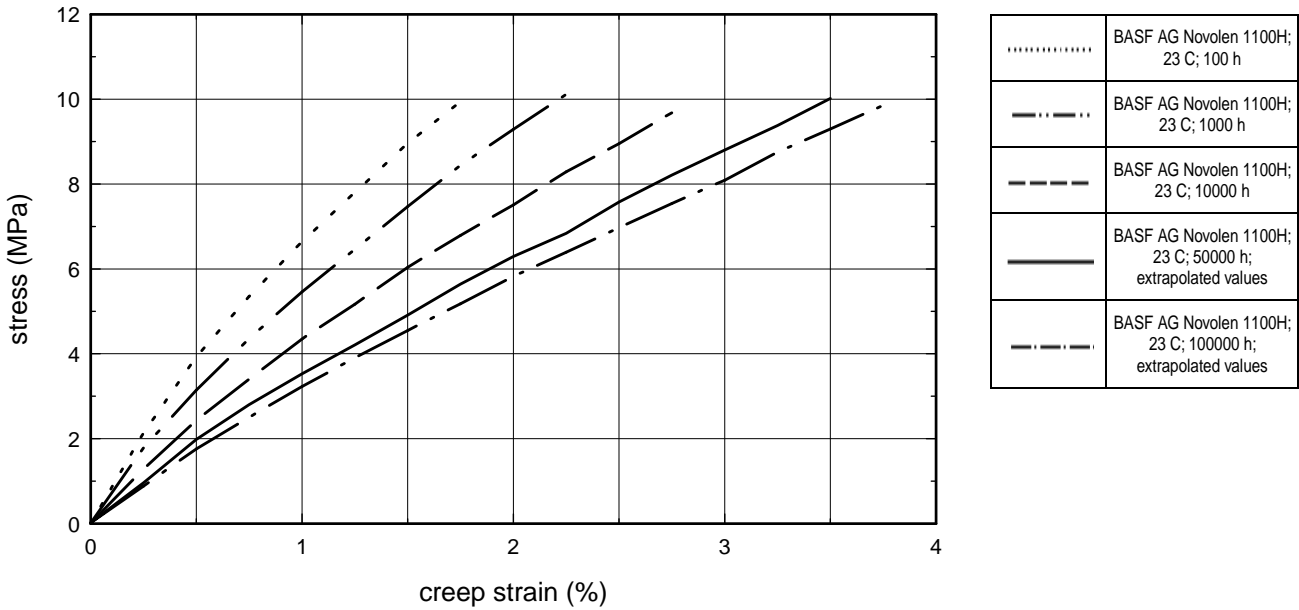
Graph 19.23 Isochronous stress vs. strain in tension @ 40°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



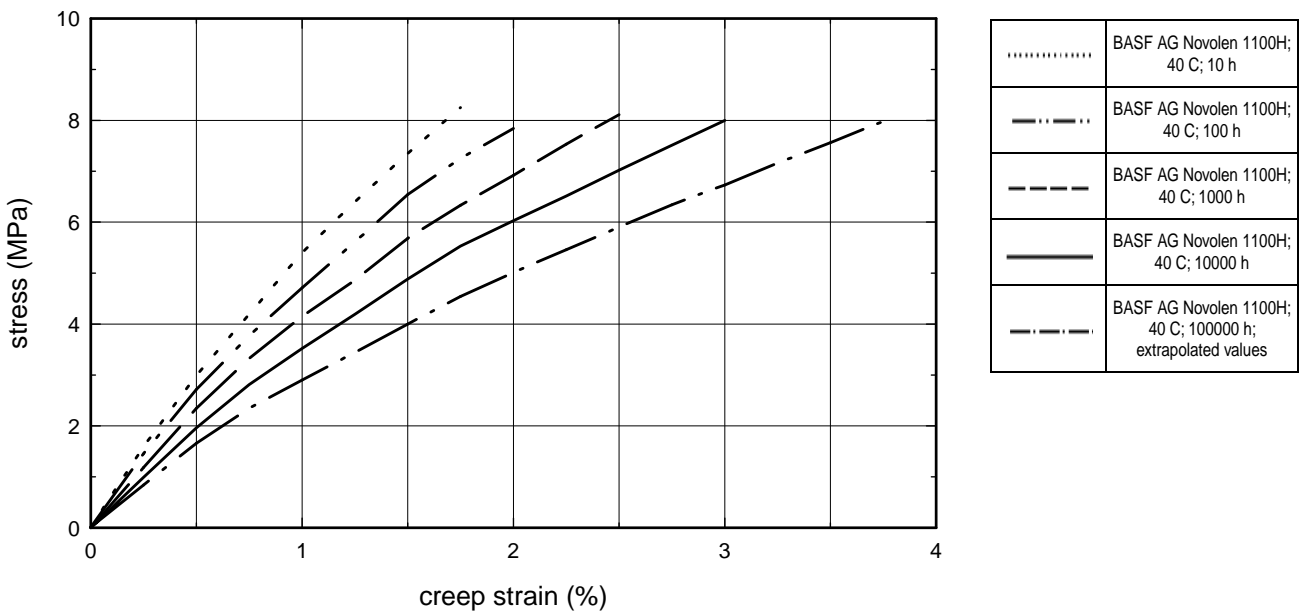
Graph 19.24 Isochronous stress vs. strain in tension @ 100°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



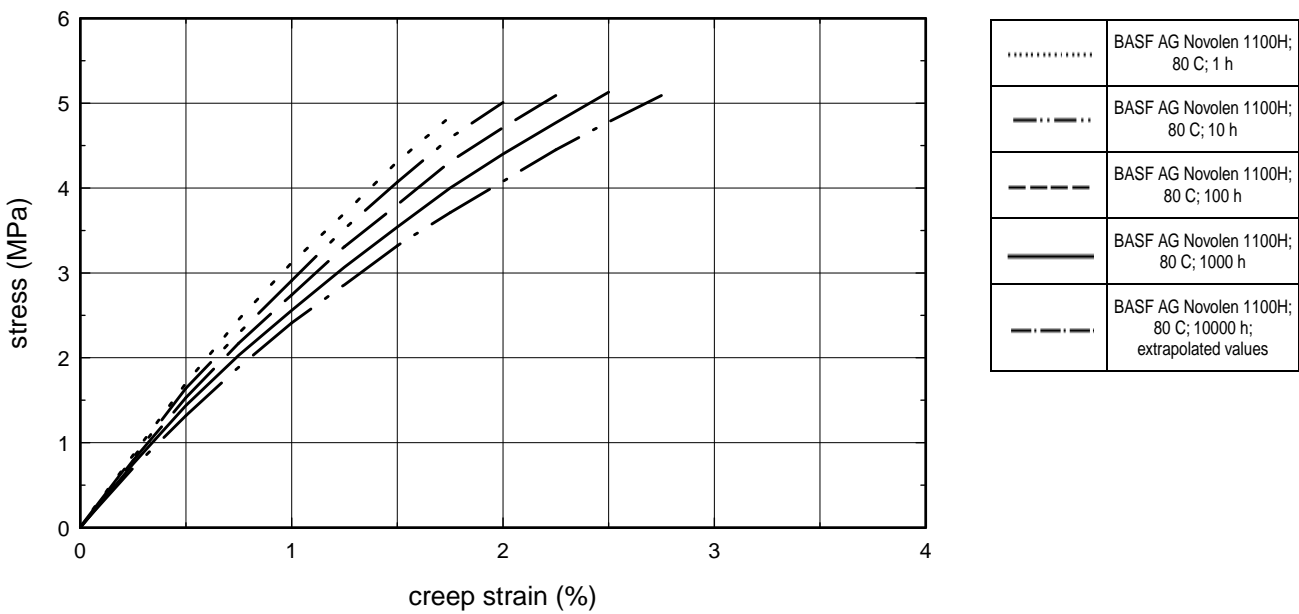
Graph 19.25 Isochronous stress vs. strain in compression @ 23°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



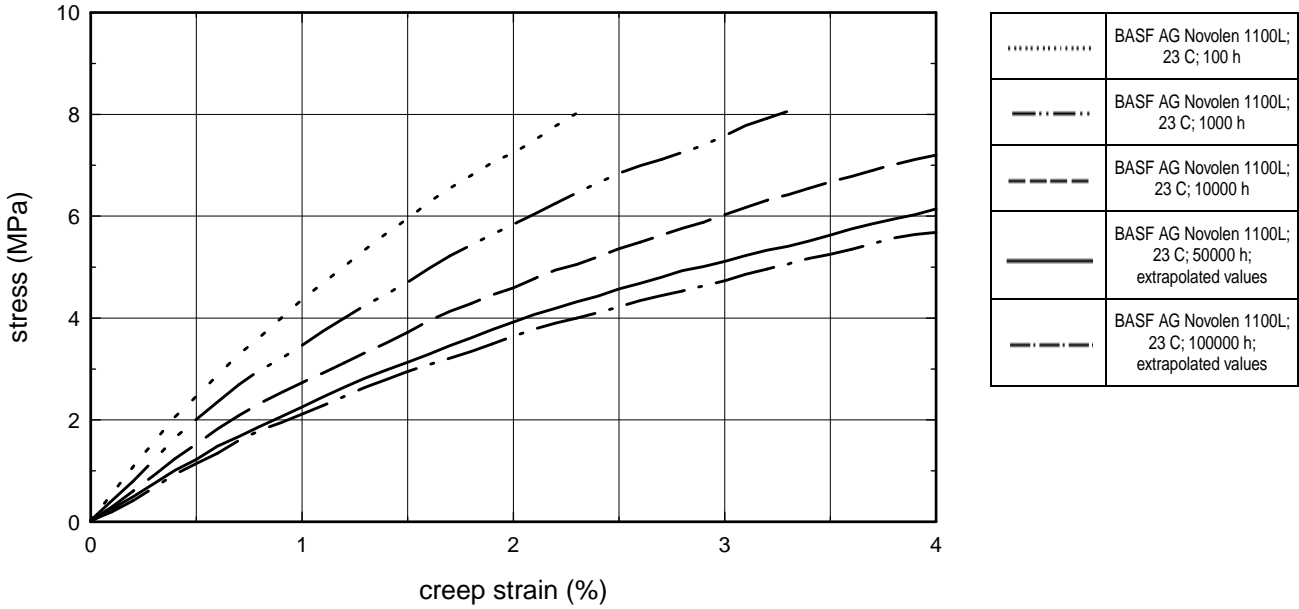
Graph 19.26 Isochronous stress vs. strain in compression @ 40°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



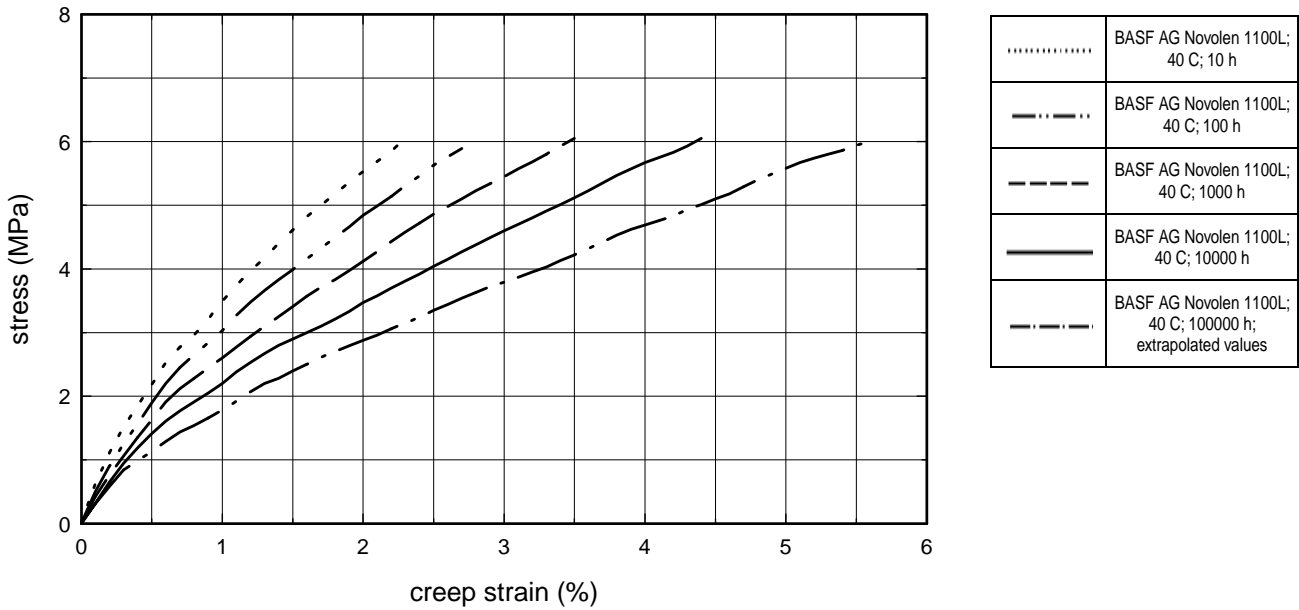
Graph 19.27 Isochronous stress vs. strain in compression @ 80°C for Novolen 1100H polypropylene (homopolymer; melt volume index: 2.5 cc/10 min. @ 230°C, 2.16 kg, 4 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



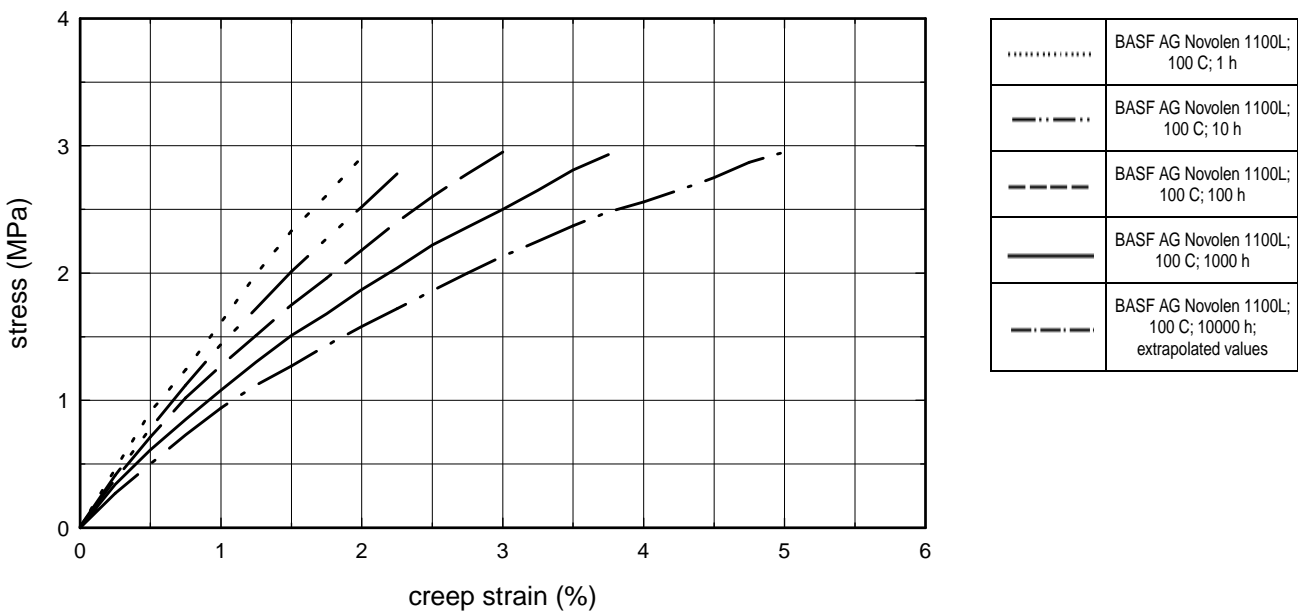
Graph 19.28 Isochronous stress vs. strain in tension @ 23°C for Novolen 1100L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 13 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



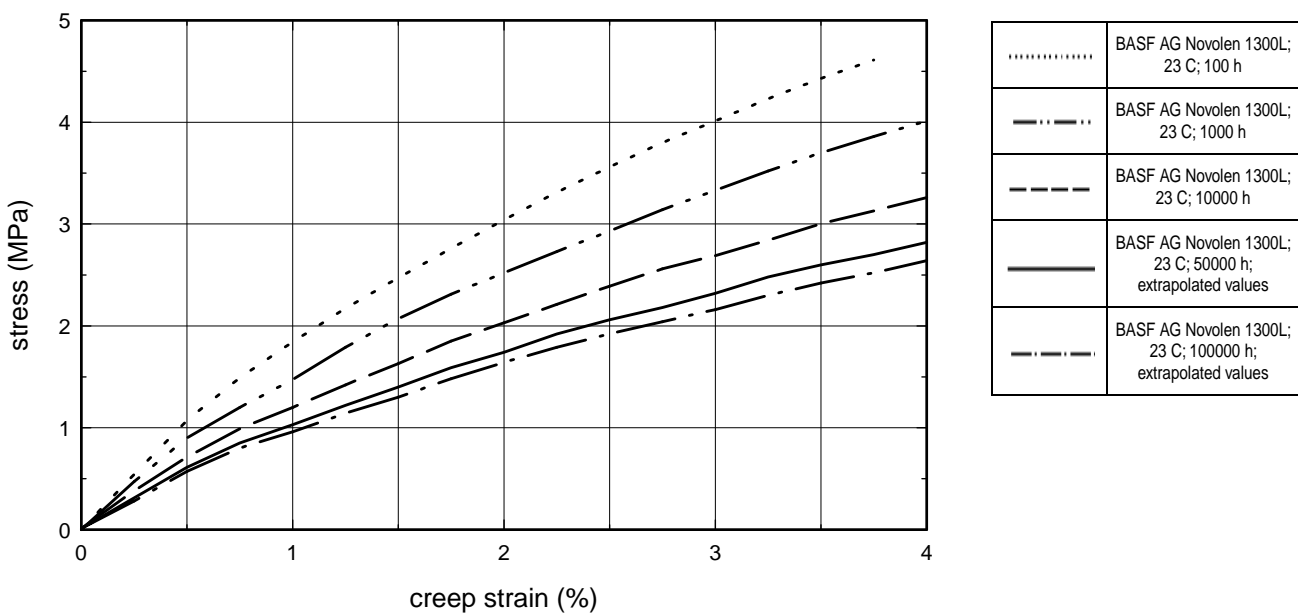
Graph 19.29 Isochronous stress vs. strain in tension @ 40°C for Novolen 1100L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 13 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



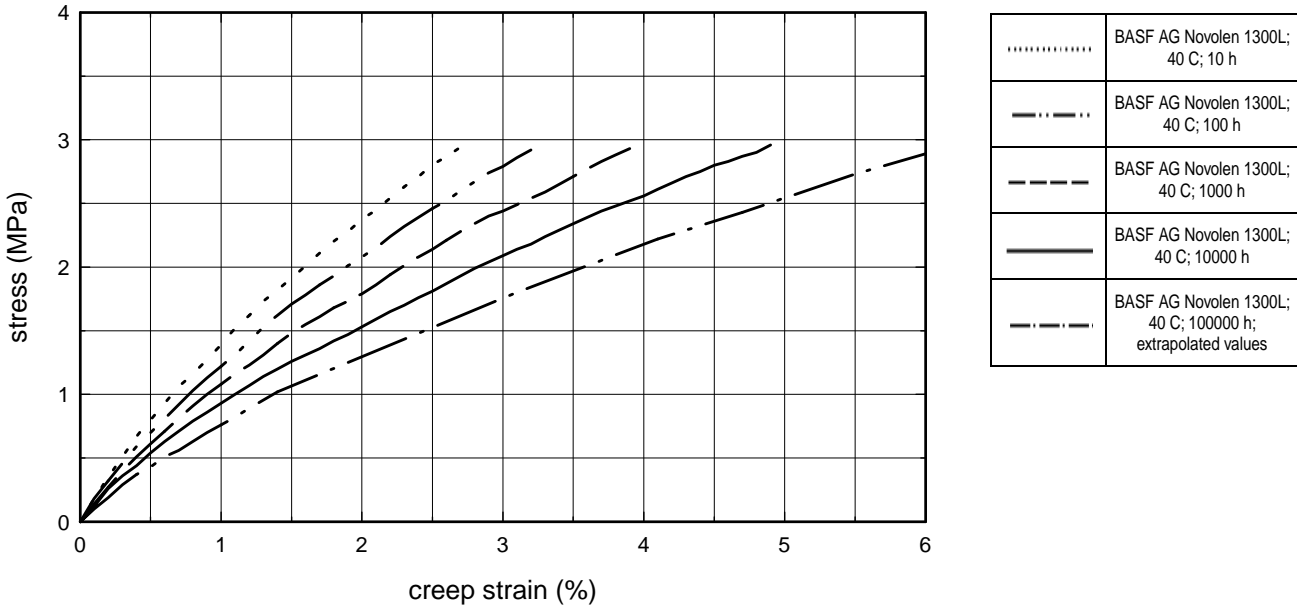
Graph 19.30 Isochronous stress vs. strain in tension @ 100°C for Novolen 1100L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 13 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



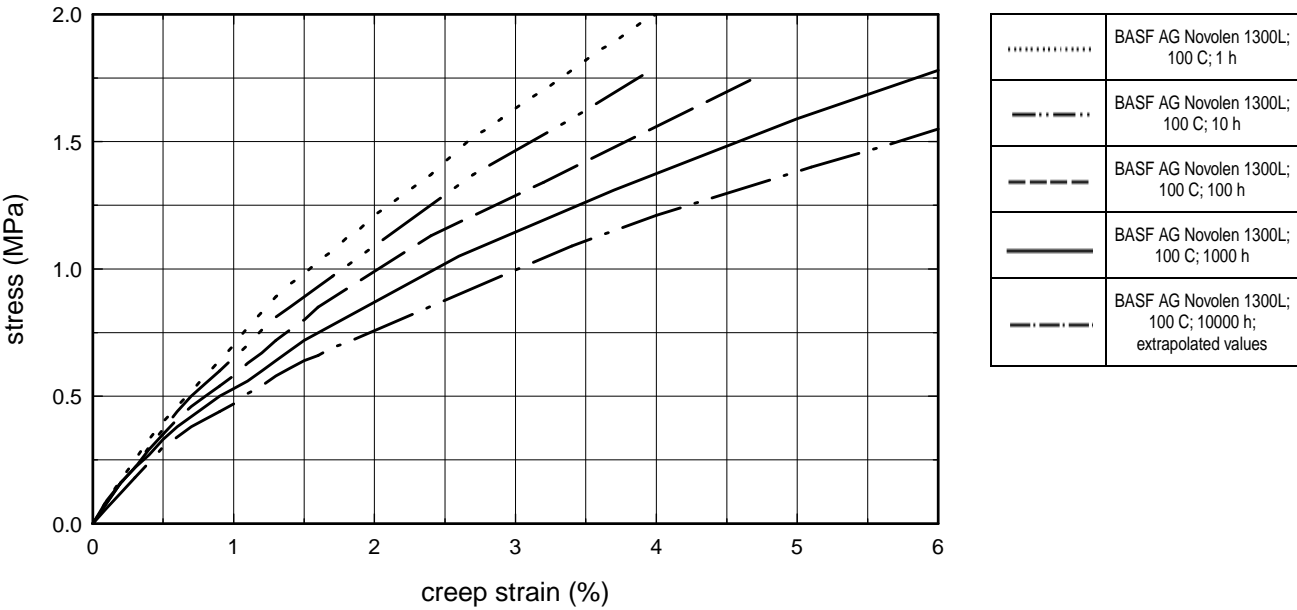
Graph 19.31 Isochronous stress vs. strain in tension @ 23°C for Novolen 1300L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 10 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



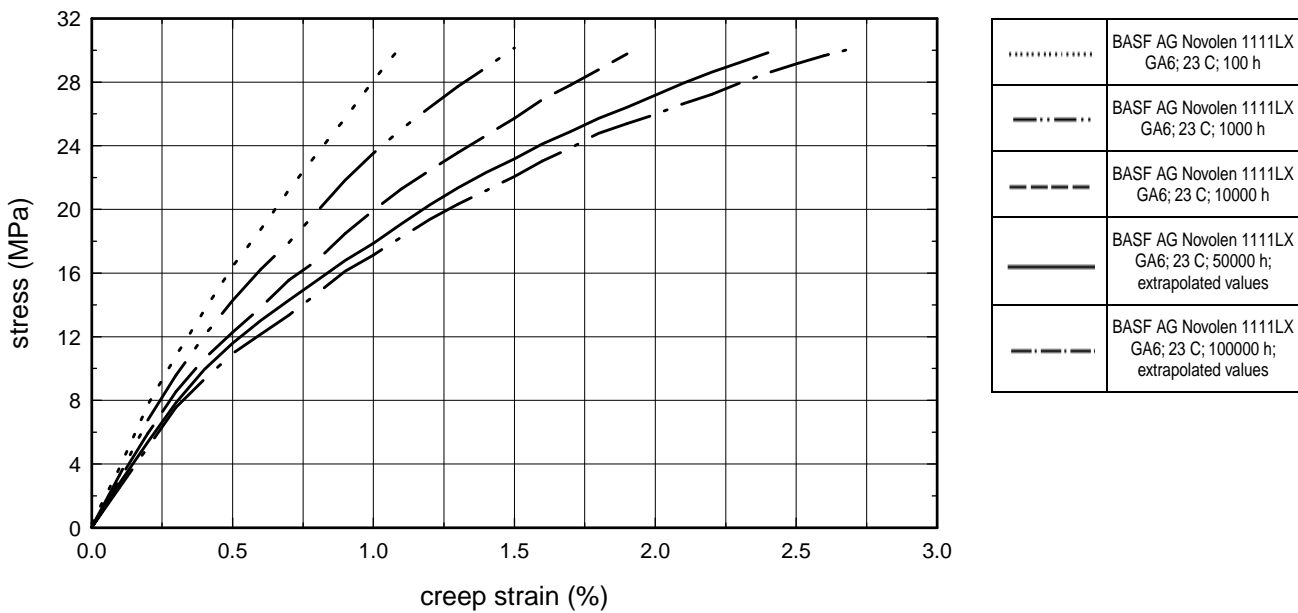
Graph 19.32 Isochronous stress vs. strain in tension @ 40°C for Novolen 1300L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 10 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



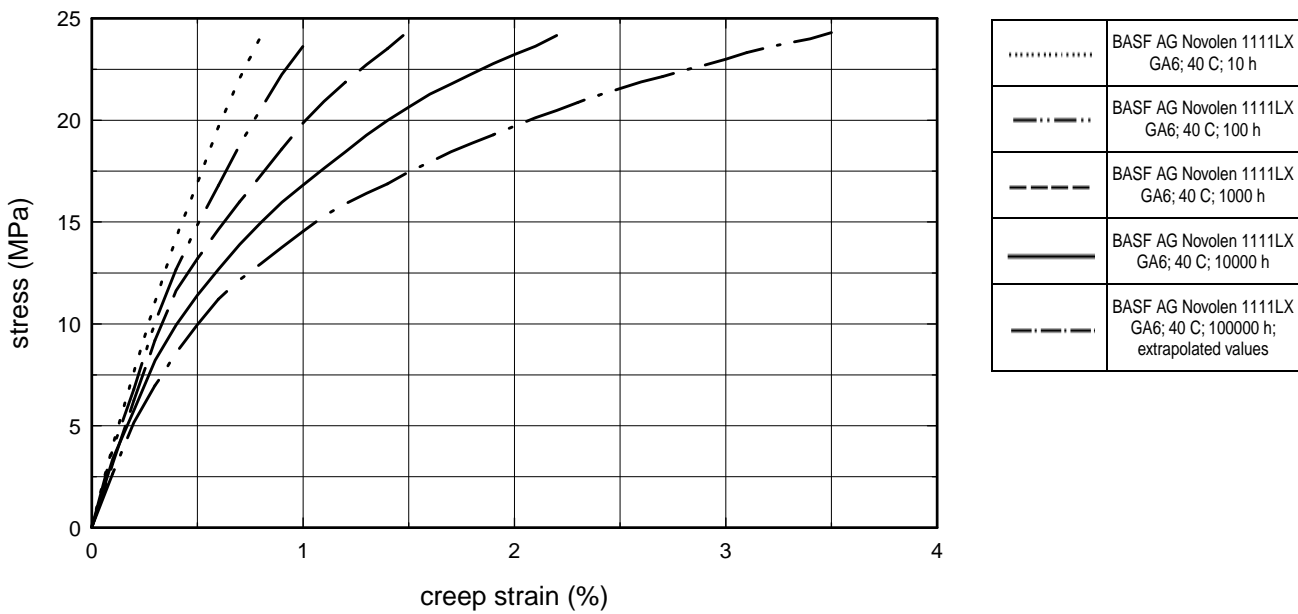
Graph 19.33 Isochronous stress vs. strain in tension @ 100°C for Novolen 1300L polypropylene (homopolymer; melt volume index: 7 cc/10 min. @ 230°C, 2.16 kg, 10 cc/10 min. @190°C, 5 kg). Tested according to DIN 53444.



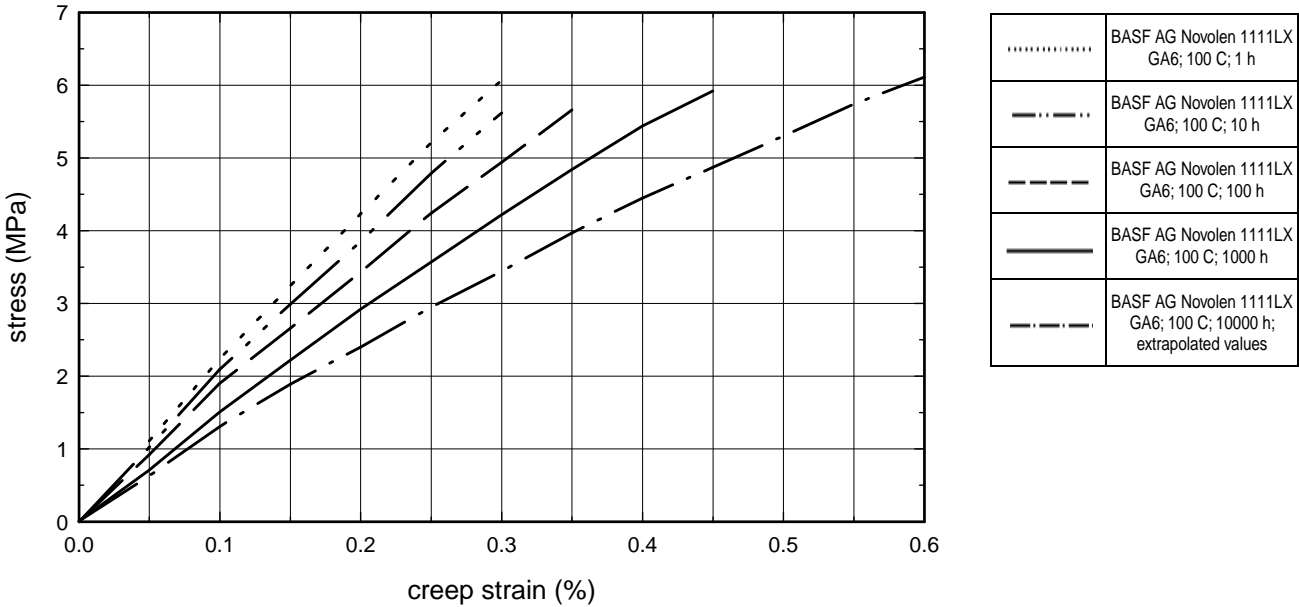
Graph 19.34 Isochronous stress vs. strain in tension @ 23°C for Novolen 1111LX GA6 polypropylene (30% glass fiber; melt volume index: 2.4 cc/10 min. @ 230°C, 2.16 kg, 5.4 cc/10 min. @ 190°C, 5 kg). Tested according to DIN 53444.



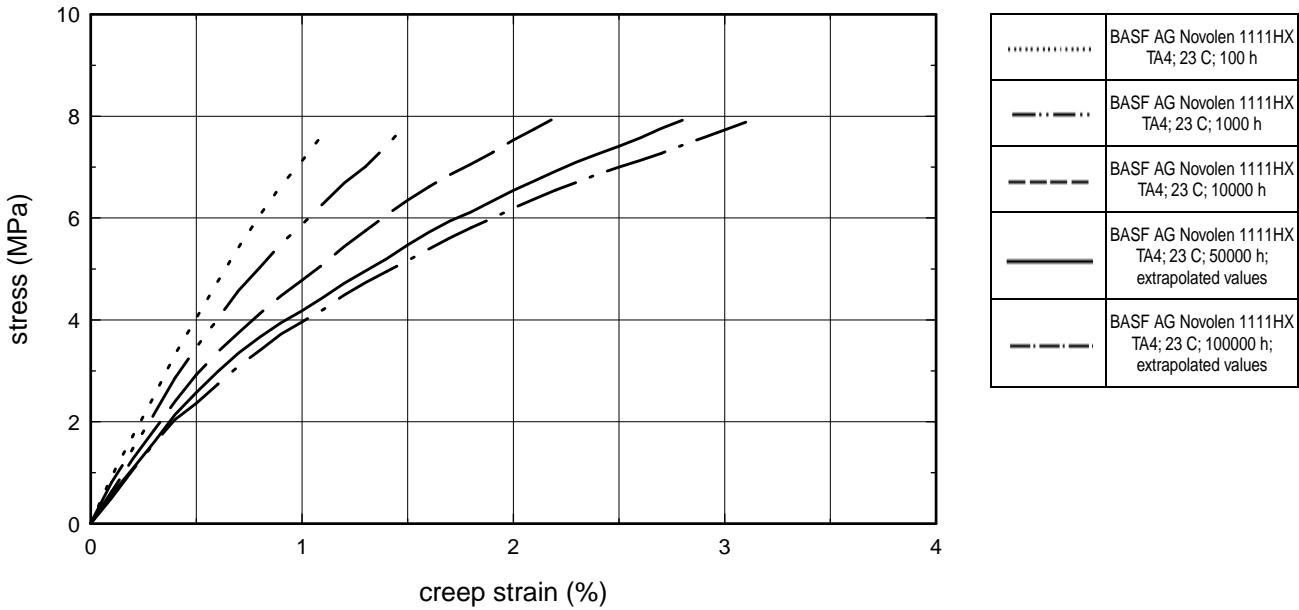
Graph 19.35 Isochronous stress vs. strain in tension @ 40°C for Novolen 1111LX GA6 polypropylene (30% glass fiber; melt volume index: 2.4 cc/10 min. @ 230°C, 2.16 kg, 5.4 cc/10 min. @ 190°C, 5 kg). Tested according to DIN 53444.



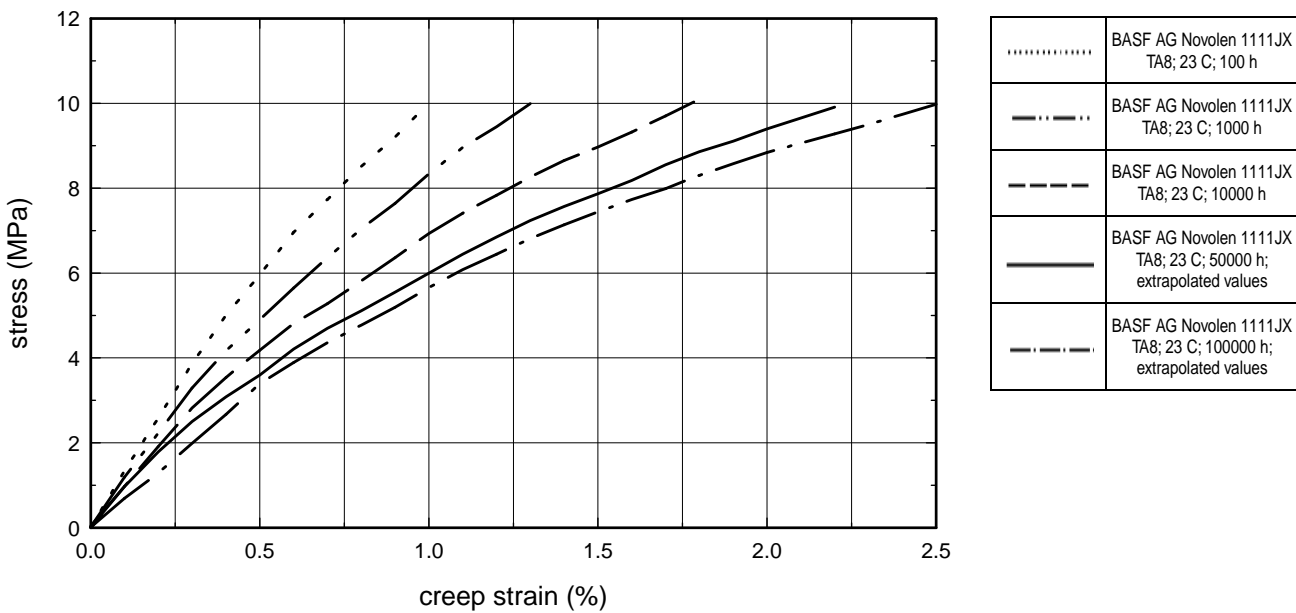
Graph 19.36 Isochronous stress vs. strain in tension @ 100°C for Novolen 1111LX GA6 polypropylene (30% glass fiber; melt volume index: 2.4 cc/10 min. @ 230°C, 2.16 kg, 5.4 cc/10 min. @ 190°C, 5 kg). Tested according to DIN 53444.



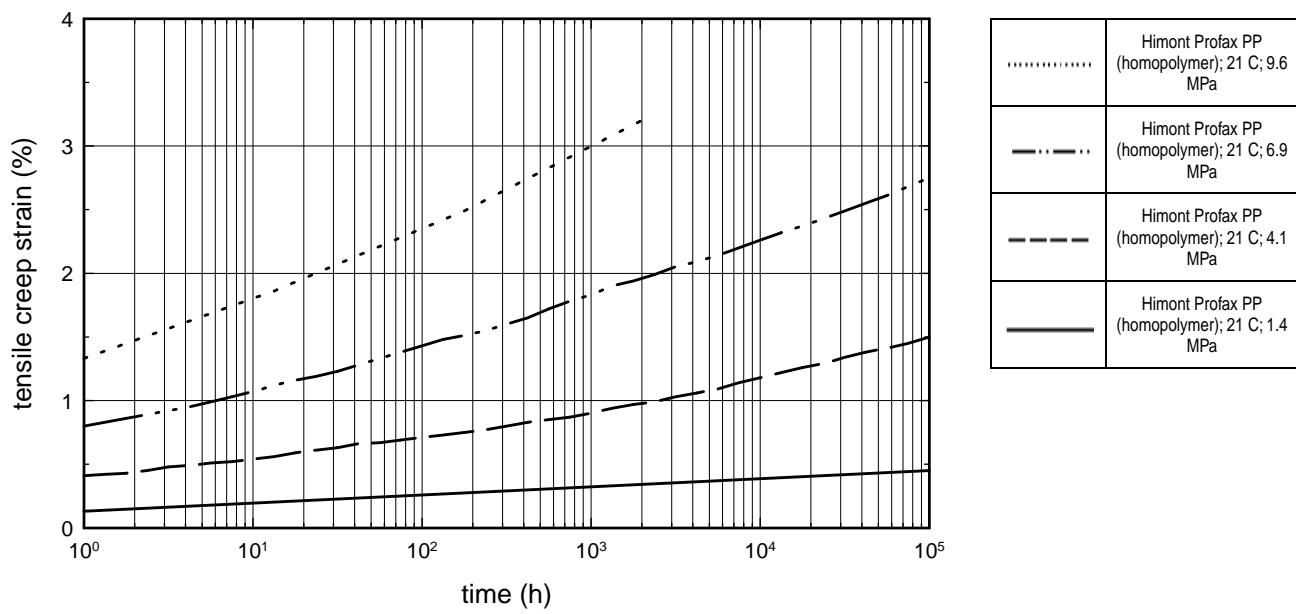
Graph 19.37 Isochronous stress vs. strain in tension @ 23°C for Novolen 1111HX TA4 polypropylene (20% mineral filler; melt flow: 5 g/10 min.). Tested according to DIN 53444.



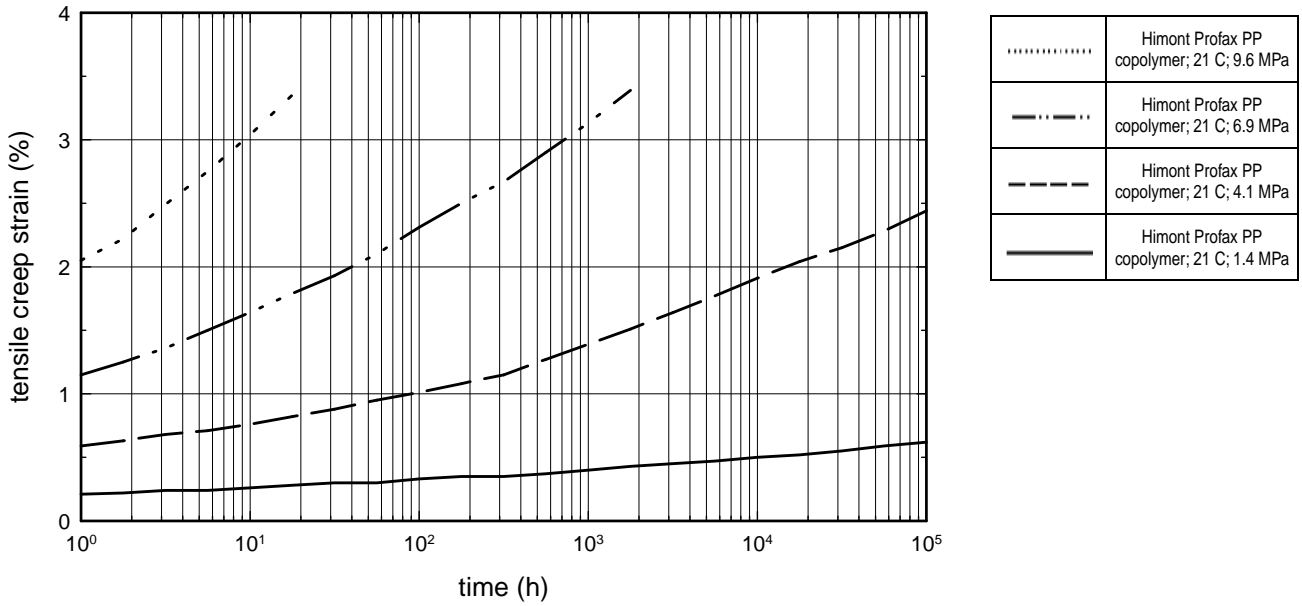
Graph 19.38 Isochronous stress vs. strain in tension @ 23°C for Novolen 1111JX TA8 polypropylene (40% mineral filler; melt flow: 5 g/10 min). Tested according to DIN 53444.



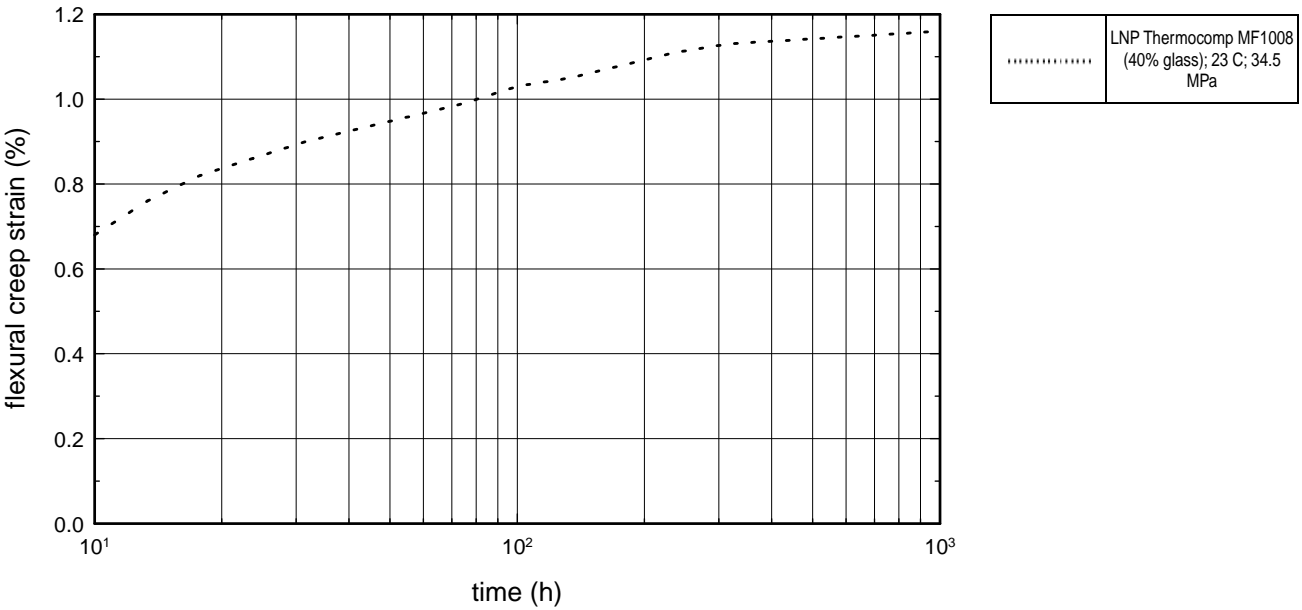
Graph 19.39 Tensile creep strain vs time for Himont Profax polypropylene (homopolymer).



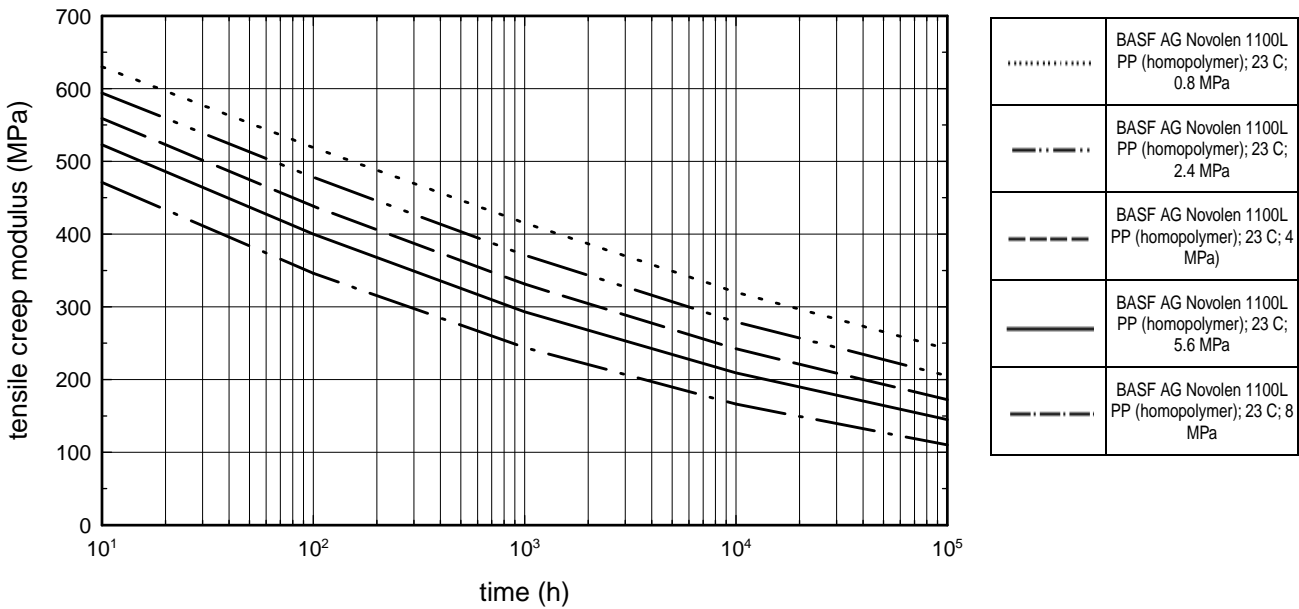
Graph 19.40 Tensile creep strain vs time for Himont Profax polypropylene copolymer.



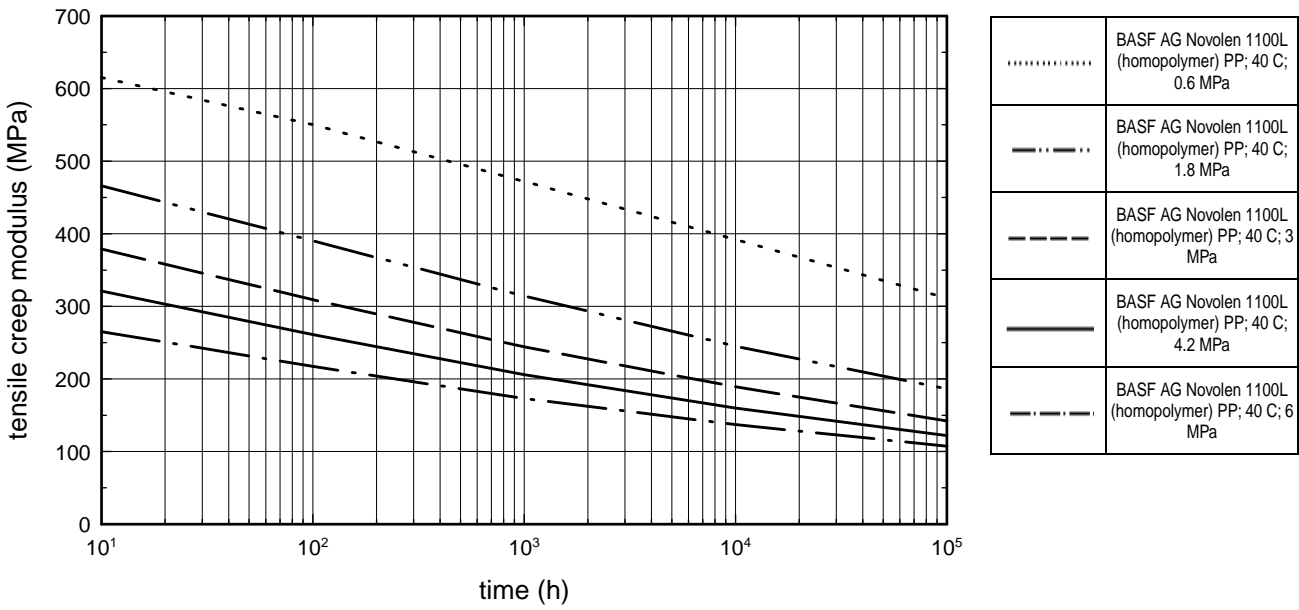
Graph 19.41 Flexural creep strain vs time for LNP Thermocomp MF1008 40% glass reinforced polypropylene.



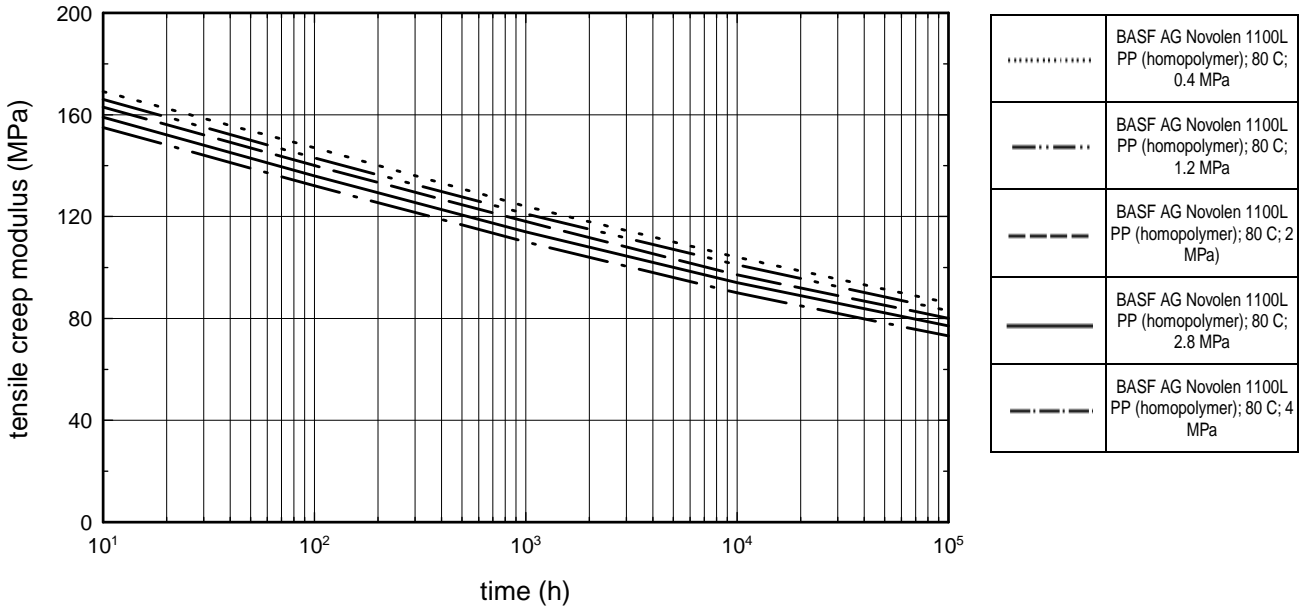
Graph 19.42 Tensile creep modulus vs. time at 23°C for BASF AG Novolen 1100L polypropylene homopolymer.



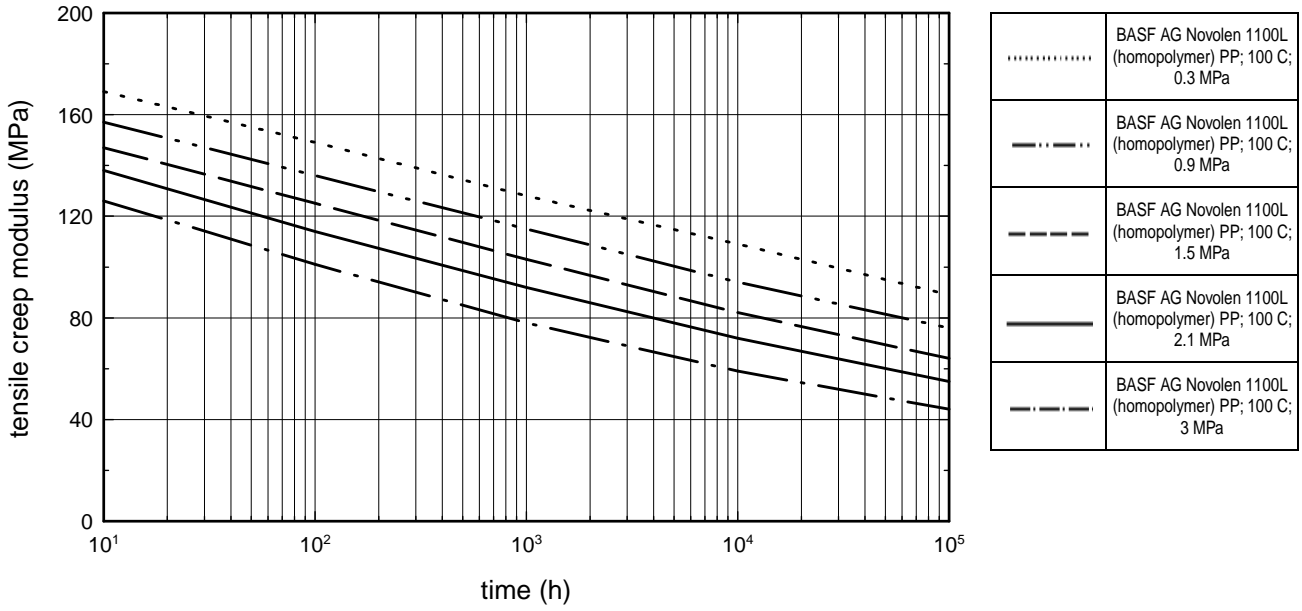
Graph 19.43 Tensile creep modulus vs. time at 40°C for BASF AG Novolen 1100L polypropylene homopolymer.



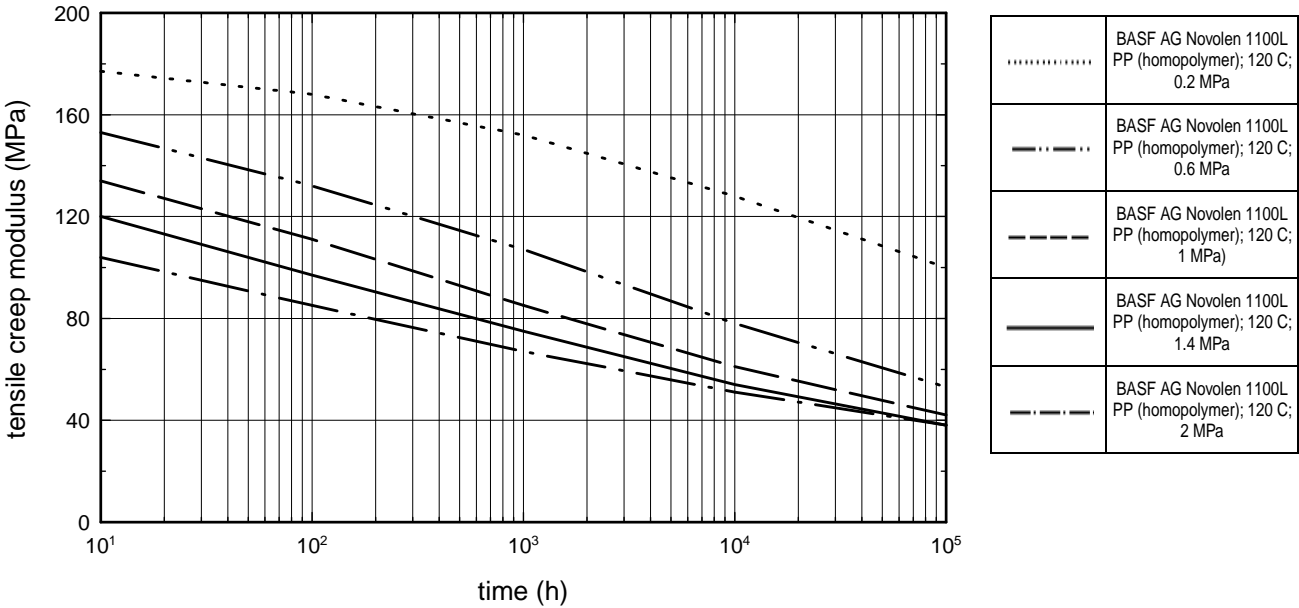
Graph 19.44 Tensile creep modulus vs. time at 80°C for BASF AG Novolen 1100L polypropylene homopolymer.



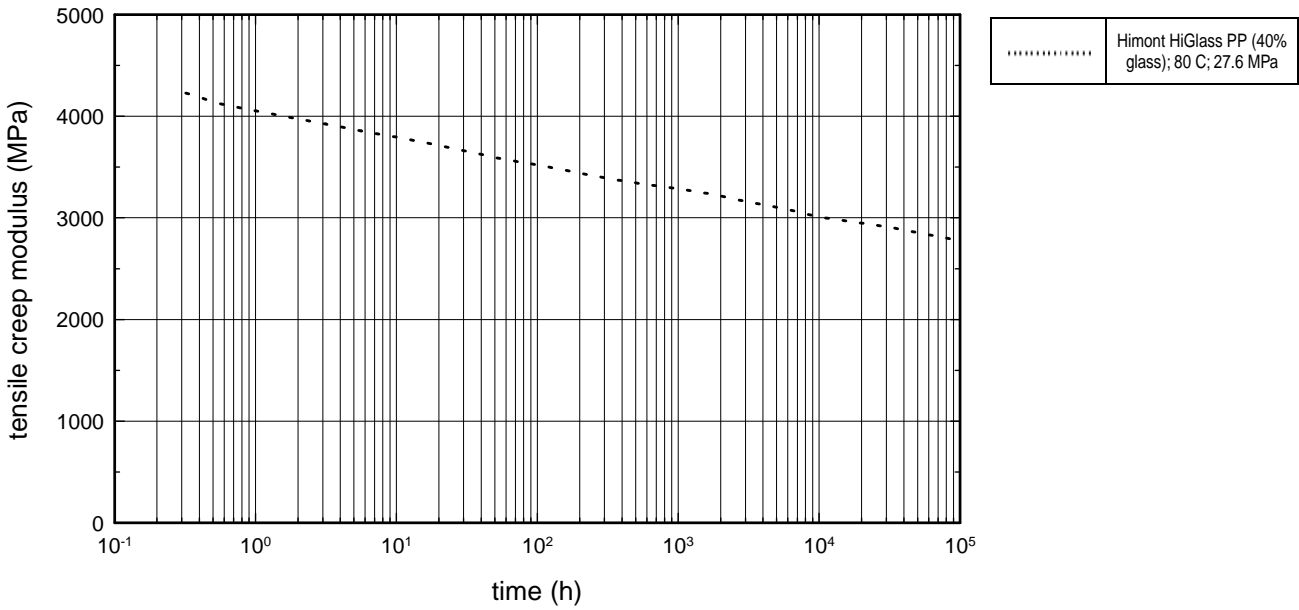
Graph 19.45 Tensile creep modulus vs. time at 100°C for BASF AG Novolen 1100L polypropylene homopolymer.



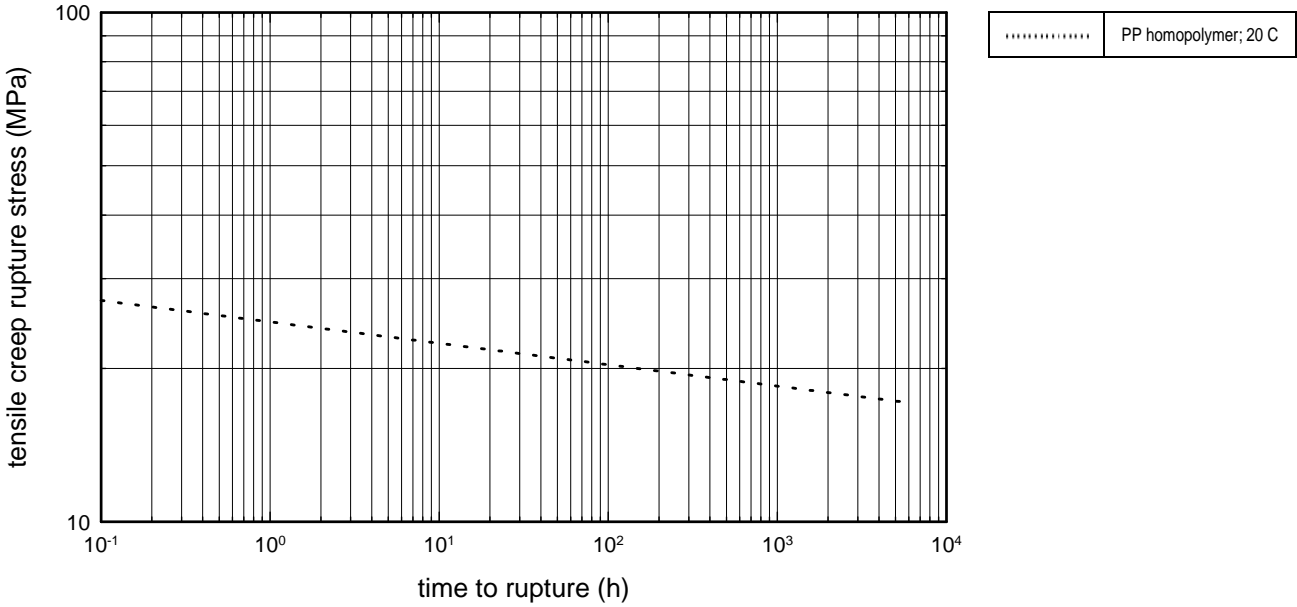
Graph 19.46 Tensile creep modulus vs. time at 120°C for BASF AG Novolen 1100L polypropylene homopolymer.



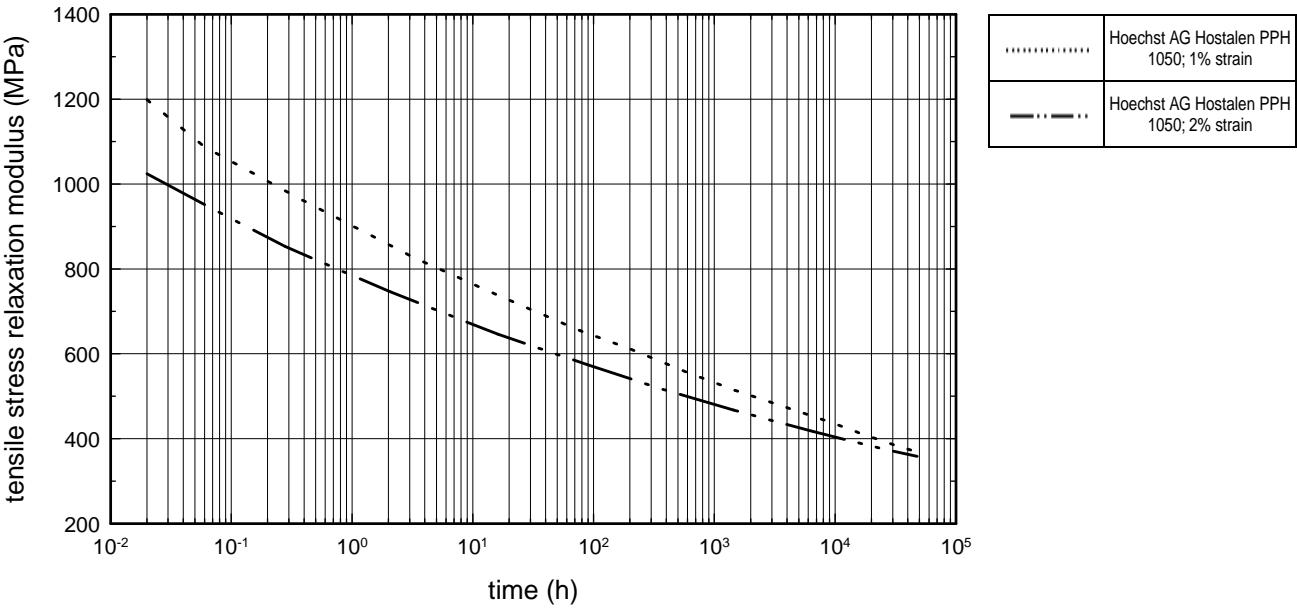
Graph 19.47 Tensile creep modulus vs. time at 80°C and 27.6 MPa for Himont HiGlass 40% glass fiber reinforced polypropylene.



Graph 19.48 Typical tensile creep rupture stress vs time to rupture @ 20°C for polypropylene homopolymer (source: R.Kahl, 1979, paper from Principles of Plastics Materials seminar, Center for Professional Advancement).

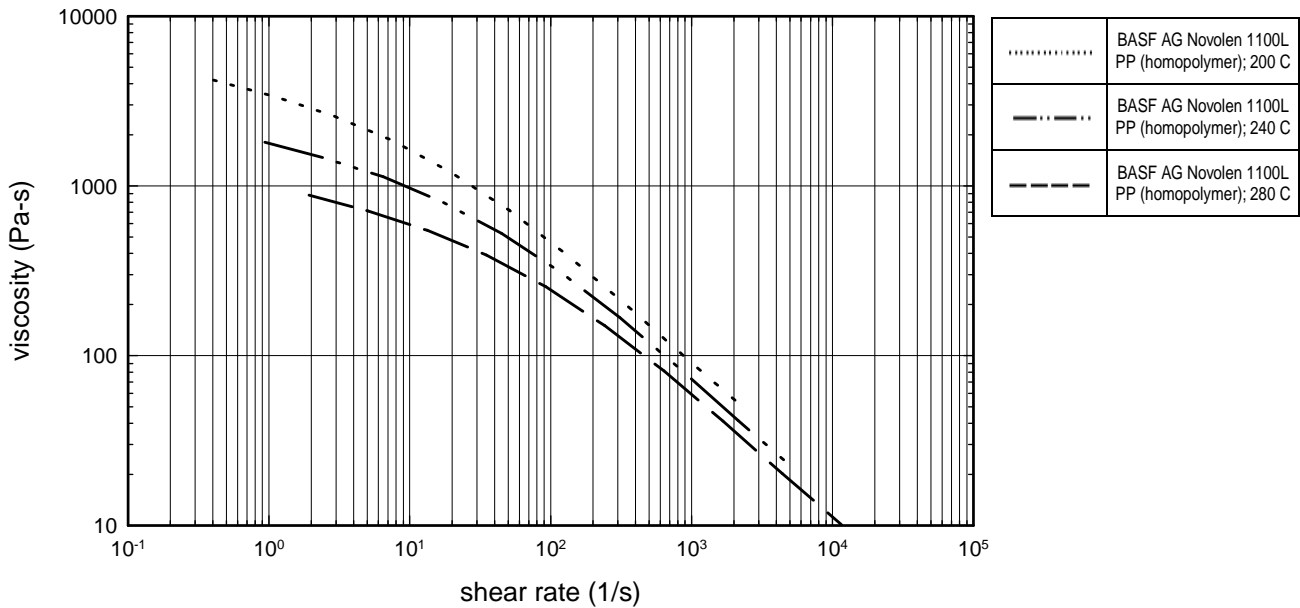


Graph 19.49 Tensile stress relaxation modulus vs time for Hoechst AG Hostalen PPH 1050 polypropylene homopolymer.

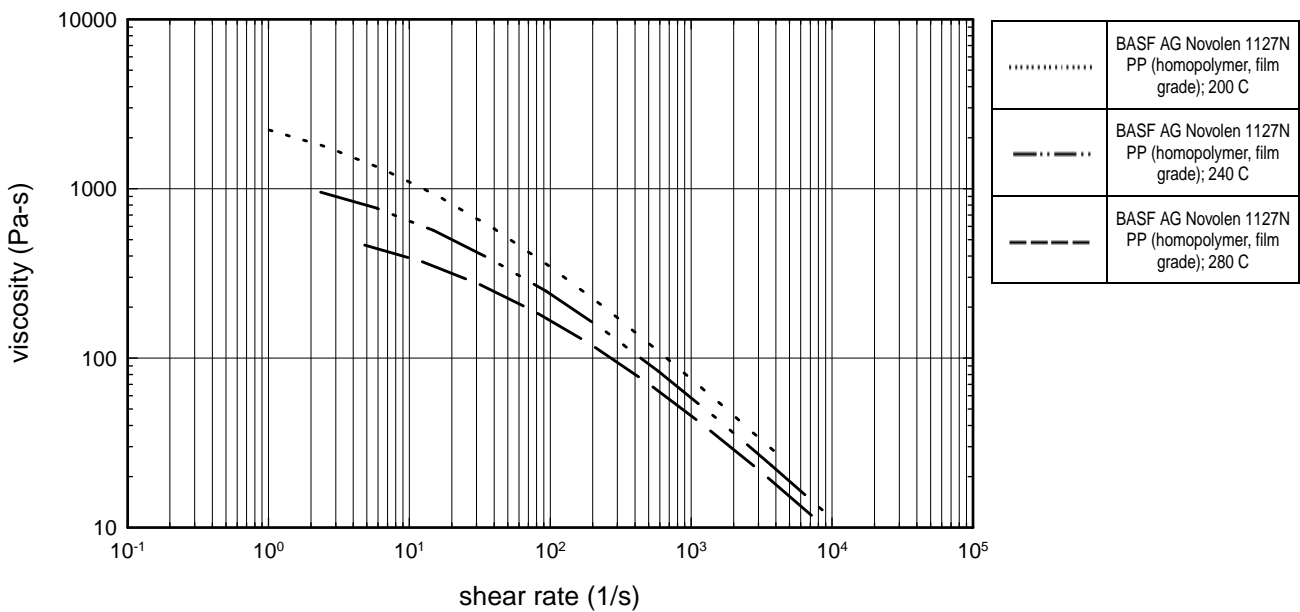


19.8 Viscosity

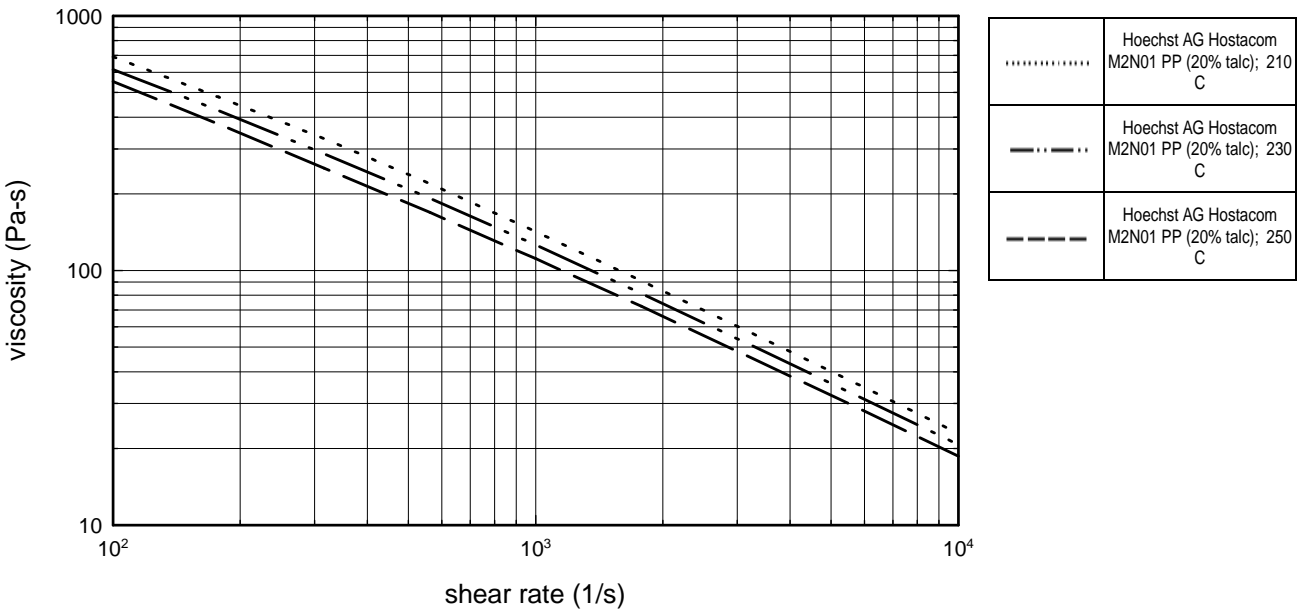
Graph 19.50 Viscosity vs. shear rate for BASF AG Novolen 1100L polypropylene homopolymer.



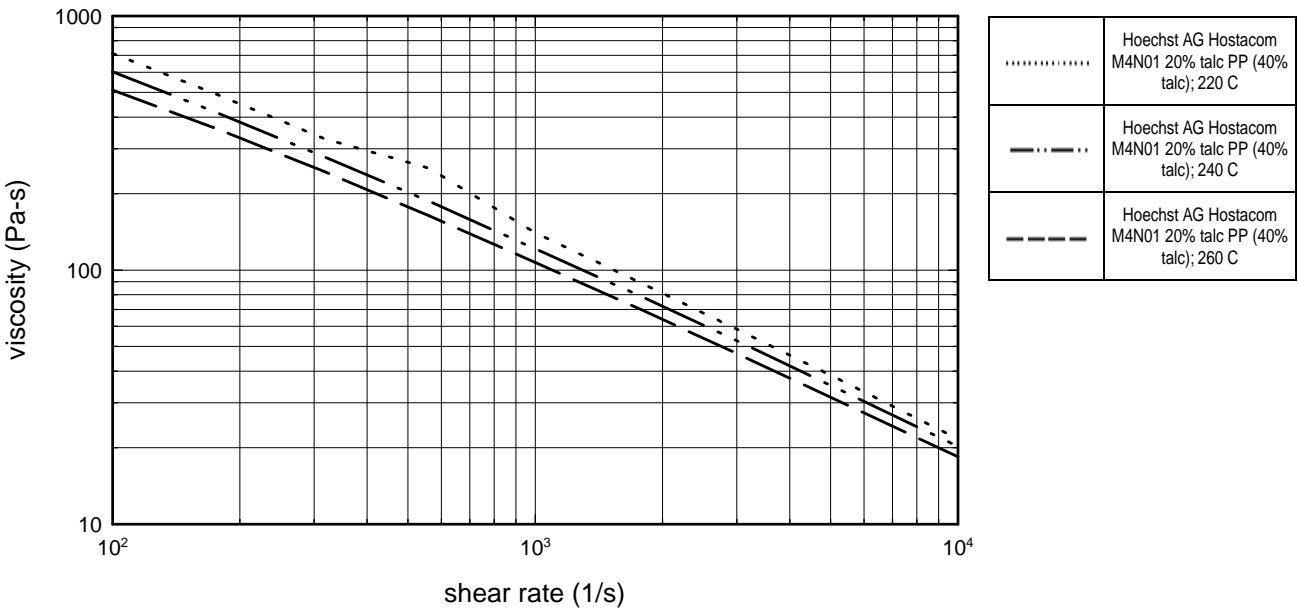
Graph 19.51 Viscosity vs. shear rate for BASF AG Novolen 1127N polypropylene (homopolymer, film grade).



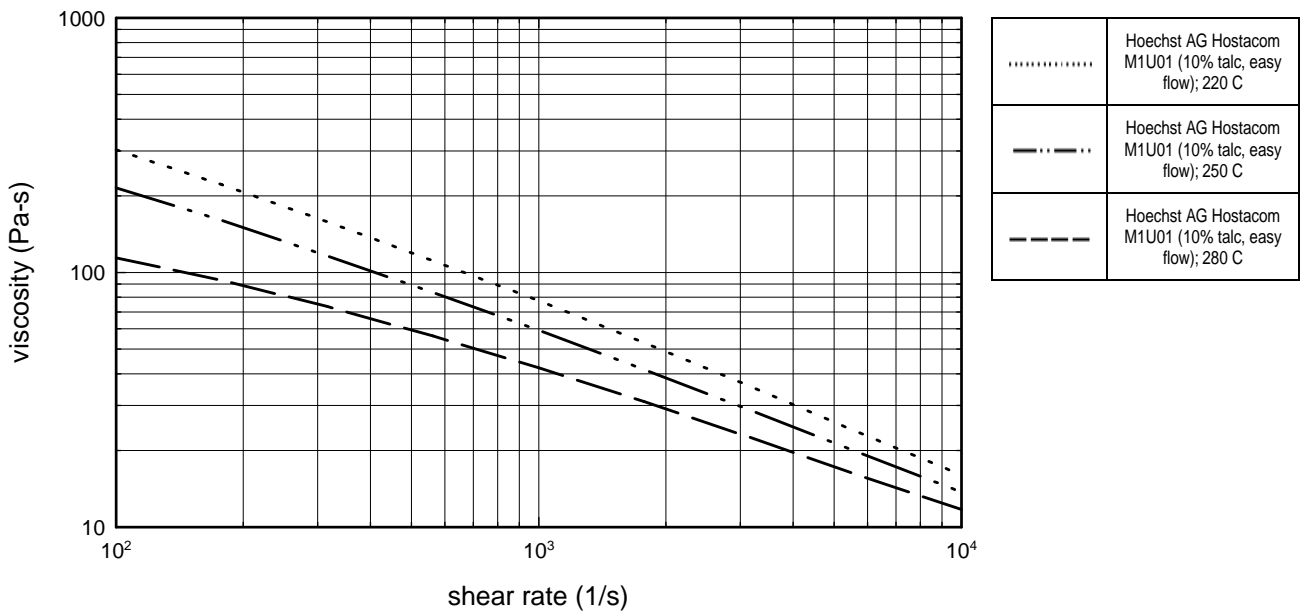
Graph 19.52 Viscosity vs. shear rate for Hoechst AG Hostacom M2N01 20% talc filled polypropylene.



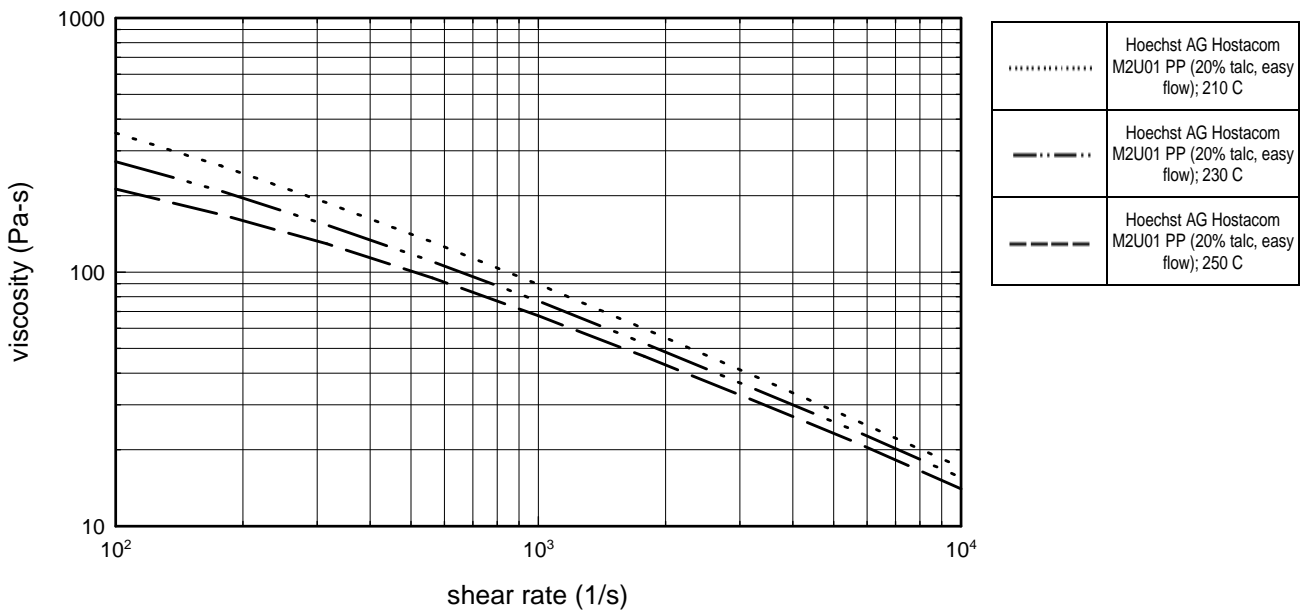
Graph 19.53 Viscosity vs. shear rate for Hoechst AG Hostacom M4N01 40% talc filled polypropylene.



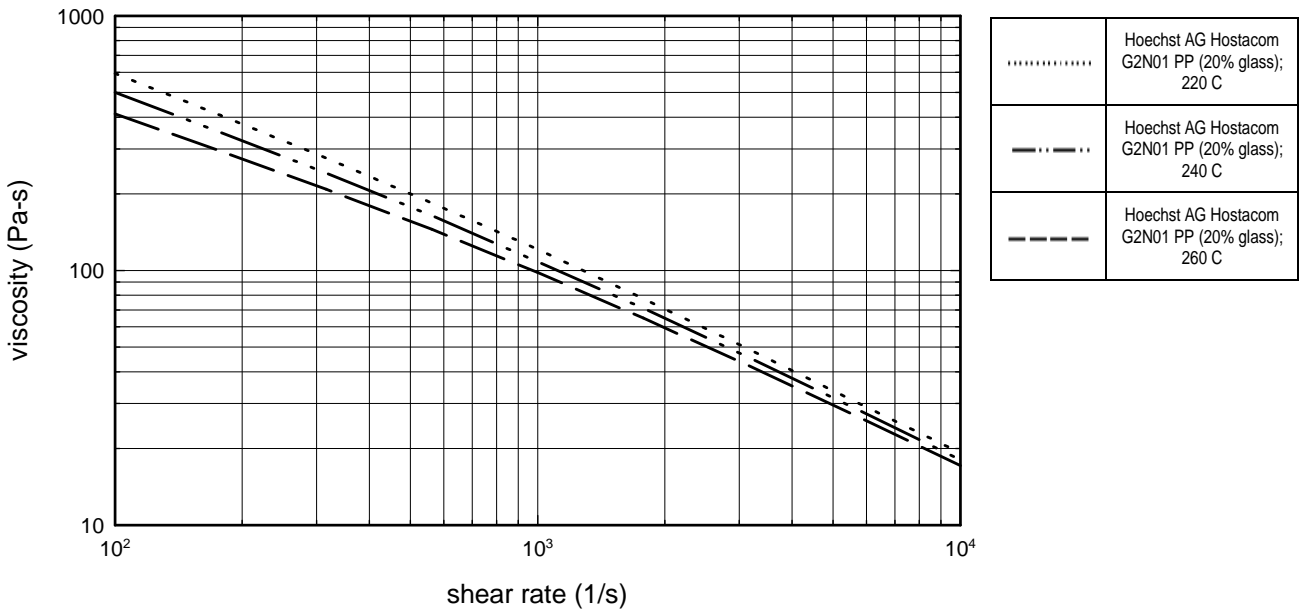
Graph 19.54 Viscosity vs. shear rate for Hoechst AG Hostacom M1U01 10% talc filled polypropylene.



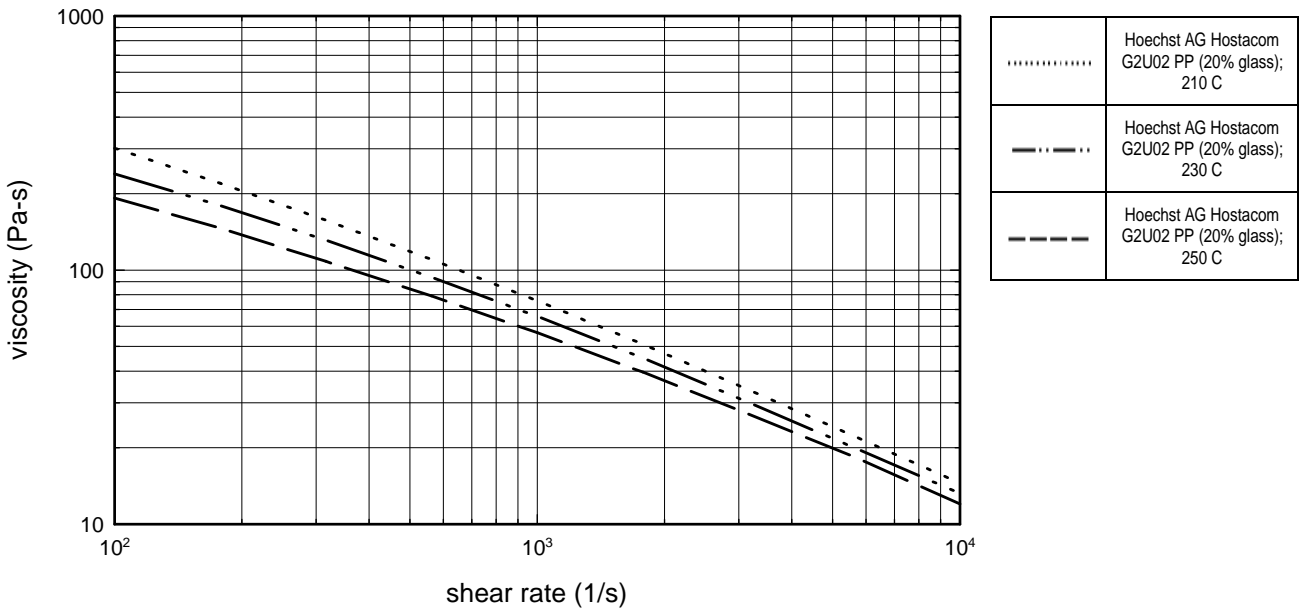
Graph 19.55 Viscosity vs. shear rate for Hoechst AG Hostacom M2U01 20% talc filled polypropylene.



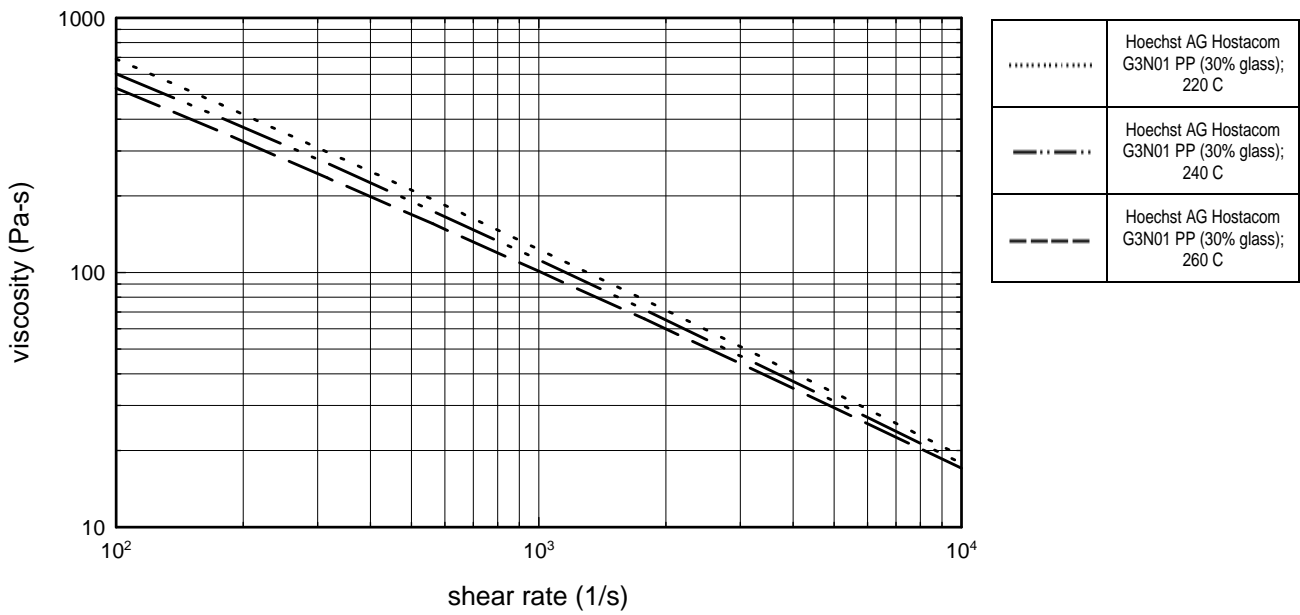
Graph 19.56 Viscosity vs. shear rate for Hoechst AG Hostacom G2N01 20% glass fiber reinforced polypropylene.



Graph 19.57 Viscosity vs. shear rate for Hoechst AG Hostacom G2U02 20% glass fiber reinforced polypropylene.

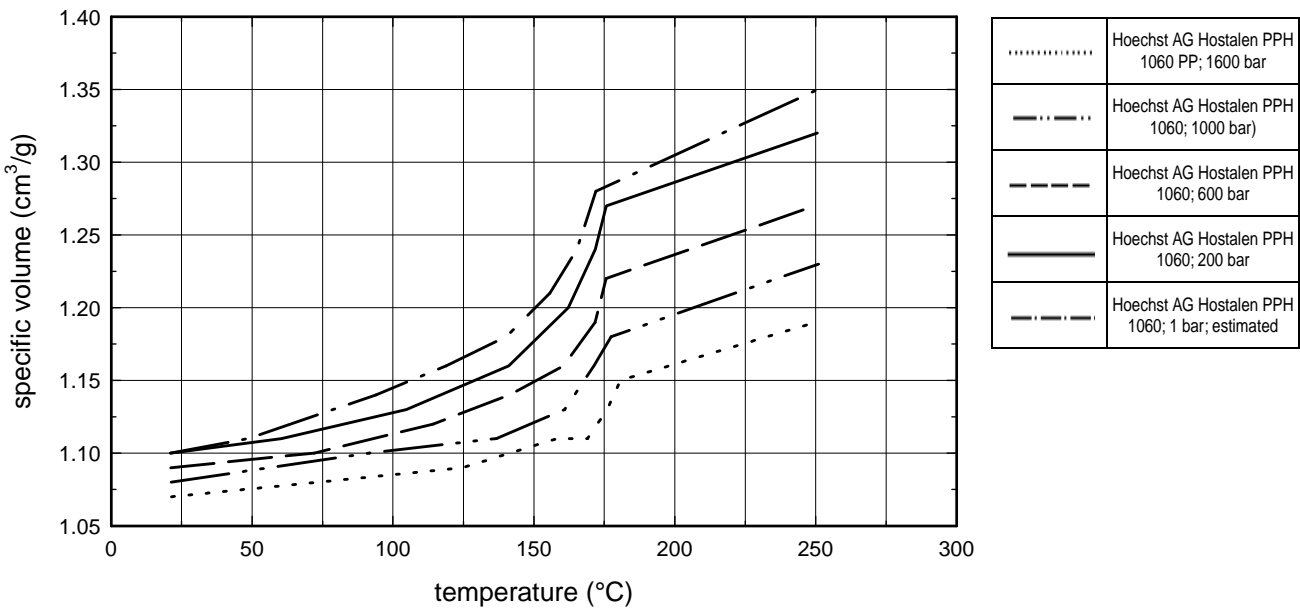


Graph 19.58 Viscosity vs. shear rate for Hoechst AG Hostacom G3N01 30% glass fiber reinforced polypropylene.

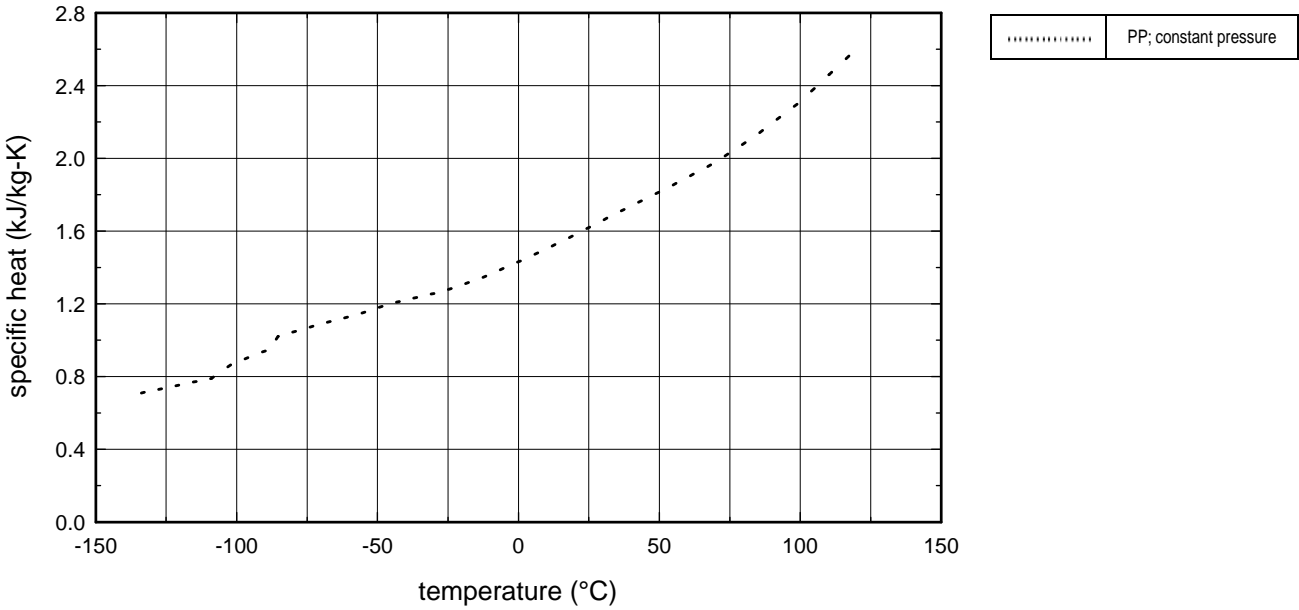


19.9 Thermodynamic Property

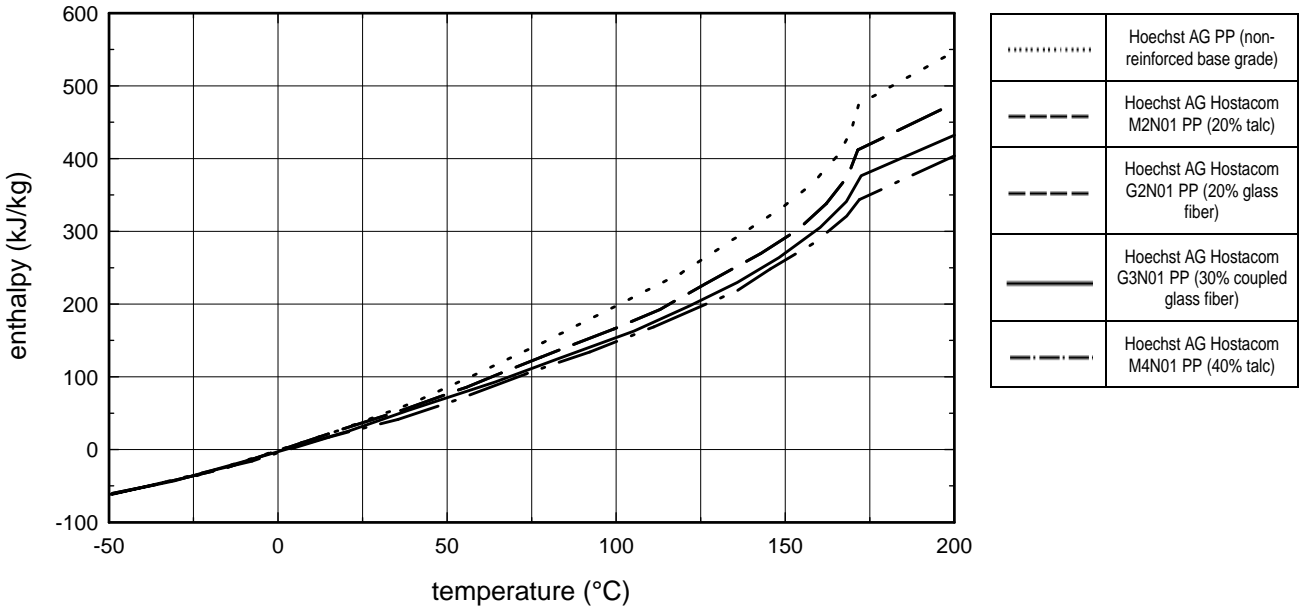
Graph 19.59 Specific volume vs temperature for Hoechst AG Hostalen PPH 1060 polypropylene homopolymer. Measured during heating up.



Graph 19.60 Specific heat vs temperature for polypropylene at constant pressure.



Graph 19.61 Enthalpy vs temperature for Hoechst AG Hostacom polypropylene.



19.10 Fatigue

Examples of materials subject to fatigue loading include a snap action plastic latch which is constantly opened and closed, a reciprocating mechanical part on a machine, a gear tooth, a bearing, any structural component subjected to vibration or any part which will be subjected to repeated impacts. Less obvious examples of components subject to fatigue loading include an air line filter bowl subjected to on off pressurizations of less than 10 times per day or a hot water kettle which is subjected to the stresses of heating and cooling at the rate of perhaps two times per day.

Estimates in the literature indicate that between 20% and 80% of plastic part service failures can be attributed to fatigue. Despite the importance of dynamic fatigue failure in plastics, very little has been done to standardize test methods, thereby leading to many different approaches. The problem is that there are many variables which affect test results and to cover them all in a comprehensive test program for even one material is an impossible task.

In fatigue testing, a specimen of the material being tested is subjected to repeated cycles of short term stress or deformation. Eventually, microcracks or defects form in the specimen's structure, causing decreased toughness, impact strength, and tensile elongation — and the likelihood of failure at stress levels considerably lower than the material's original ultimate tensile strength. The number of cycles to failure at any given stress level depends on the inherent strength of the resin, the size and number of defects induced at that stress level, the environment of the test specimen and the conditions under which the material was tested.

Typical fatigue tests are conducted on a machine which subjects a cantilever beam to reverse flexural loading cycles at different maximum stress levels. Fatigue tests are also made in tension, compression, alternating tension and compression, cycling around zero stress, cycling superimposed on a static preload and at constant deformation or constant load. The number of cycles to failure is recorded for each stress level. The data are generally presented in a plot of log stress versus log cycles called an S-N curve. Significant differences in the S-N curve can be produced by testing at different frequencies, different mean stresses, different waveforms, and different test methods, i.e., tension rather than bending. Therefore, appropriate test conditions should be reported with the curve.

Although fatigue test data give some indication of the relative ability of plastic materials to survive failure, the designer must be aware of the above variables. The tests are run on specially prepared samples in a test environment which never resembles the actual loading and environment of the actual parts. Therefore, it is essential that tests be run on actual injection molded parts under end use operating conditions to determine the true fatigue endurance of any part subjected to cyclic loading.

Nevertheless fatigue test data resembling end use conditions are helpful in understanding plastics fatigue performance, ranking materials and qualitatively guiding design. Fatigue data are also useful in measuring the effects of the many variables that affect fatigue performance of plastics such as frequency, temperature and loading conditions.

19.10.1 Factors Affecting Fatigue Performance

Depending on the stress amplitude and the frequency of load application, fatigue failure of polymers can occur by two means, thermal fatigue failure and mechanical fatigue failure. Thermal fatigue failure involves thermal softening (or yielding), which precedes crack propagation leading to ultimate failure. This mechanism dominates in certain materials at large stress amplitudes within a particular range of frequency of load applications. At a lower stress amplitude, on the other hand, a conventional form of fatigue crack propagation (FCP) mechanism is generally observed. Low frequency is also found to cause fatigue fracture by conventional crack propagation at high stress amplitude.

Polymer fatigue behavior is generally sensitive to temperature, frequency, and environment, as well as molecular weight, molecular weight density and aging. S-N curves that do not account for these effects should be used with caution. Fatigue resistance will also be affected by processing history since ease of crack initiation depends upon whether flaws or imperfections are present in the material. Good particulate dispersion or avoidance of residual stresses/ strains by correct processing effectively improves the resistance to fatigue failure of the resulting components.

The high damping and low thermal conductivity of polymers cause a strong dependency of temperature rise on the rate of load application (frequency) and on the deformation level (stress or strain amplitude). From a thermodynamic point of view, part of the mechanical work done during cy-

clic loading is spent on irreversible molecular processes, leading to microscopic deformations such as crazes, shear bands, voids, and microcracks. The other part of the mechanical work evolves as heat. Both processes are obviously interdependent.

19.10.2 Fatigue Properties

Eastman: Tenite Polypropylene possesses a unique characteristic — the ability to be molded or formed into a tough and highly fatigue resistant one piece hinge. A properly formed integral hinge in polypropylene is very strong, even though the hinge area is usually the thinnest part of the entire article. The superior strength results from the molecular orientation induced in the hinge by flexing. Flexing the hinge causes the molecules to align themselves perpendicular to the hinge, concentrating the molecular chain strength in the direction of alignment. Unoriented molecular chains have a random configuration which distributes the chain strength in all directions. If practical, the hinge should be flexed as soon after forming as possible since the molecules can be oriented much easier, and the possibility of breakage is reduced, if the hinge is flexed while it retains heat imparted to it during the forming operation.

Reference: Utilizing Inherent Hinge Properties of Tenite Polypropylene and Tenite Polyallomer, supplier technical report (TR-14E) — Eastman Chemical, 1987.

19.10.3 Effect of Glass Reinforcement on Fatigue Behavior

LNP Engineering Plastics: Verton MFX-700-10 HS (material composition: 50% glass fiber reinforcement; note: long glass fibers (average fiber length of 1330-1370 microns), chemically coupled glass fibers); **Verton MFX-7006 HS** (material composition: 30% glass fiber reinforcement; note: long glass fibers, chemically coupled glass fibers); **Verton MFX-7008 HS** (material composition: 40% glass fiber reinforcement; note: chemically coupled glass fibers, long glass fibers)

The flexural fatigue behavior of 30%, 40%, and 50% long glass-reinforced polypropylene composites was tested. Under static testing conditions there is a pronounced difference in tensile properties with numbers ranging from 107 MPa to 128 MPa, but as the fatigue cycles increase to 1000-10,000 cycles, all of the data converges to similar values. As the cycles increase into the million cycle region, slight differences are observed which favor the higher glass content material.

Interfacial crack initiation points are more abundant in the higher glass content material than the lower glass content material due to the greater interface area in the 50% glass-reinforced composite. Once the cracks are initiated, the crack propagation rate will be lower under higher fiber density conditions. Thus, the fatigue behavior of a 30% glass-reinforced material is characterized by fewer initiation points coupled with a faster rate of crack propagation, whereas a 50% glass reinforced composite has more initiation points along with a slower crack propagation rate. As the cycles increase further, the crack propagation rate begins to have a more significant influence over the interfacial effect, and then a slightly better flexural fatigue resistance is observed in the higher glass content materials.

Reference: Grove, D.A. (LNP) m, H.C. (LNP), *Effect of Constituents on the Fatigue Behavior of Long Fiber Reinforced Thermoplastics*, ANTEC 1995, conference proceedings — Society of Plastics Engineers, 1995.

LNP Engineering Plastics: Thermocomp MFX-100-10 HS (note: chemically coupled glass fibers, short glass fiber (average length 230-280 microns)); **Verton MFX-700-10 HS** (material composition: 50% glass fiber reinforcement; note: long glass fibers (average fiber length of 1330-1370 microns), chemically coupled glass fibers)

Unlike tensile fatigue, where a uniform stress is applied across the sample, in flexural fatigue the stress varies from a large tensile stress on one side of the specimen to a large compressive stress on the opposite side. The cyclic tensile and compression loads in the outer regions lead to various levels of fiber-resin debonding coupled with some fiber breakage.

Crack initiation in glass-reinforced polypropylene composites occurred mostly due to resin-fiber debonding coupled with some fiber breakage. After the initial cracks were created, the cracks progressed towards the center of the part. The cracks would preferentially move around or pull-out the long fibers; whereas the cracks were more likely to cause pull-outs in the short fiber material.

Evidence from previous papers clearly showed that fiber pull-out, fiber breakage, etc. are part of the dominant flexural fatigue crack propagation behavior. Since longer perpendicular fibers are known to slow the progress of cracks through some pull-out, fiber breakage, and crack opening displacement criteria, the longer fiber material is expected to exhibit superior longitudinal fatigue

resistance. This behavior was indeed observed in the long glass- reinforced composites.

In the case of polypropylene, the significant resin-glass debonding behavior was the main cause for the poorer fatigue behavior of this material versus nylon and polyphthalamide. The much greater number of initial cracks formed from debonding fibers was the main reason for the poorer performance of the polypropylene material versus other composite systems.

Reference: Grove, D.A. (LNP) m, H.C. (LNP), *Effect of Constituents on the Fatigue Behavior of Long Fiber Reinforced Thermoplastics*, ANTEC 1995, conference proceedings — Society of Plastics Engineers, 1995.

19.10.4 Effect of Molecular Weight on Fatigue Behavior

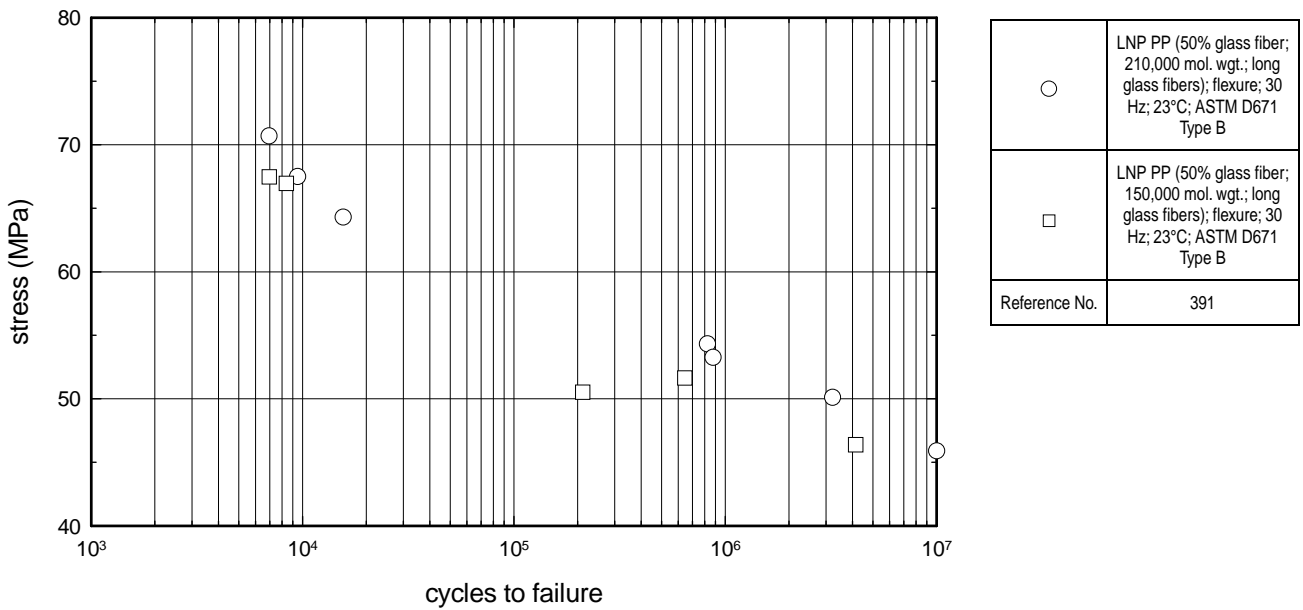
LNP Engineering Plastics: PP (material composition: 50% glass fiber reinforcement; molecular weight: 150,000; note: long glass fibers); **PP**

(material composition: 50% glass fiber reinforcement; molecular weight: 210,000; note: long glass fibers)

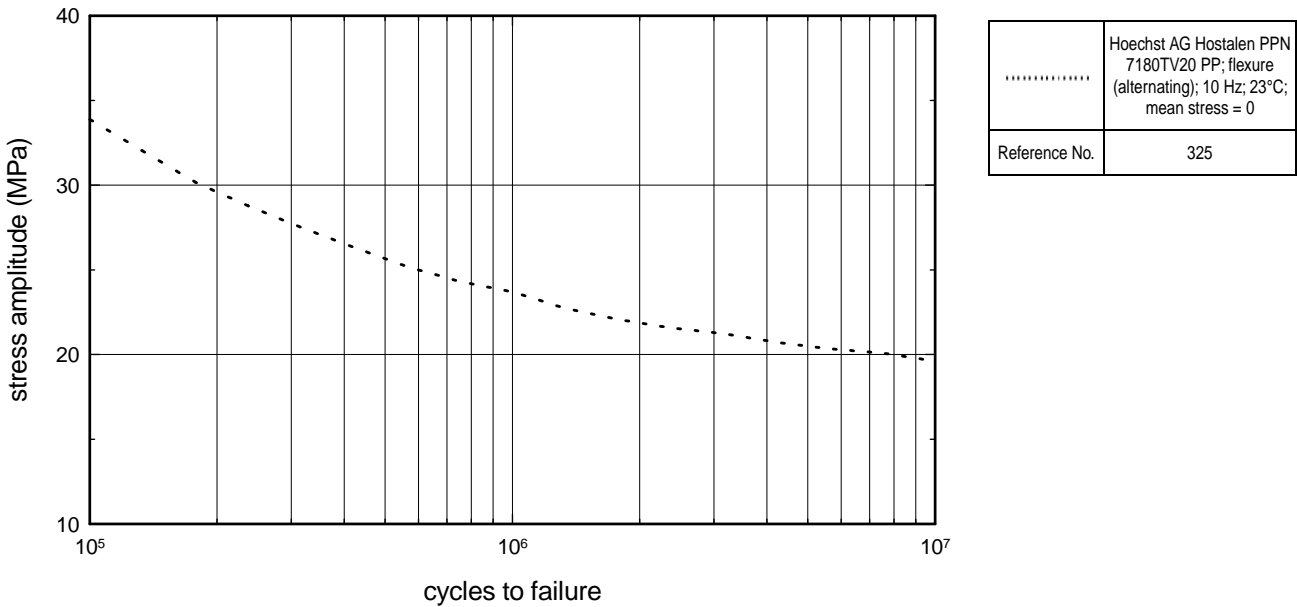
The molecular weight influence on flexural fatigue behavior was investigated by comparing the fatigue behavior of two 50% glass reinforced polypropylene composites formed from 210,000 and 150,000 weight average molecular weight polypropylene resins. Despite the employment of a lower molecular weight material, which may have adversely affected the crack propagation rate through the more brittle matrix, similar flexural fatigue behavior was observed. Perhaps, lower molecular weight polymer chains participate better in interfacial bonding to offset the increase in the expected crack propagation rate.

Reference: Grove, D.A. (LNP), Kim, H.C. (LNP), *Effect of Constituents on the Fatigue Behavior of Long Fiber Reinforced Thermoplastics*, ANTEC 1995, conference proceedings — Society of Plastics Engineers, 1995.

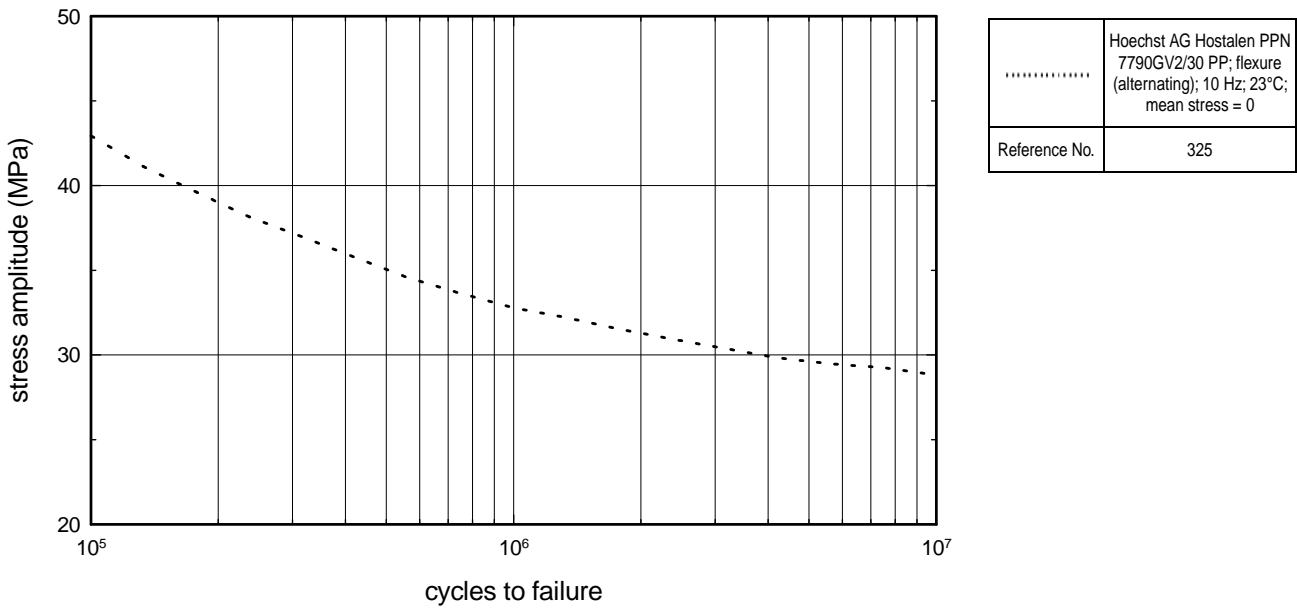
Graph 19.62 Fatigue Cycles to Failure vs. Stress in Flexure for 50% Glass Fiber Reinforced Polypropylene with Different Molecular Weights.



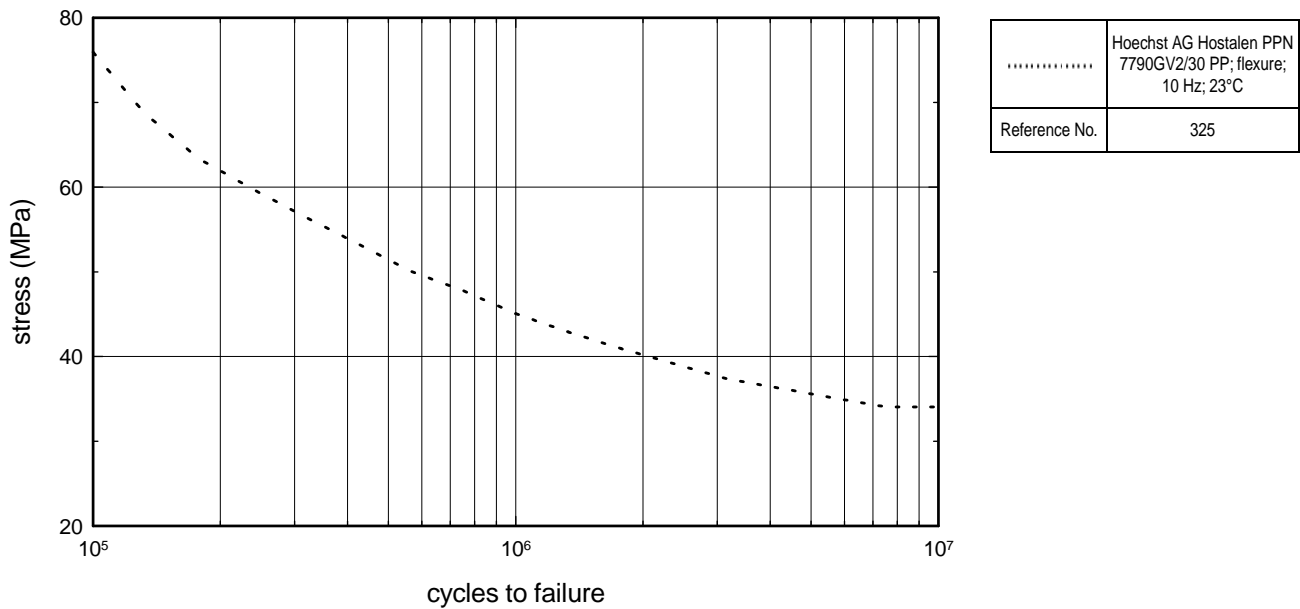
Graph 19.63 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostalen PPN 7180TV20 Polypropylene.



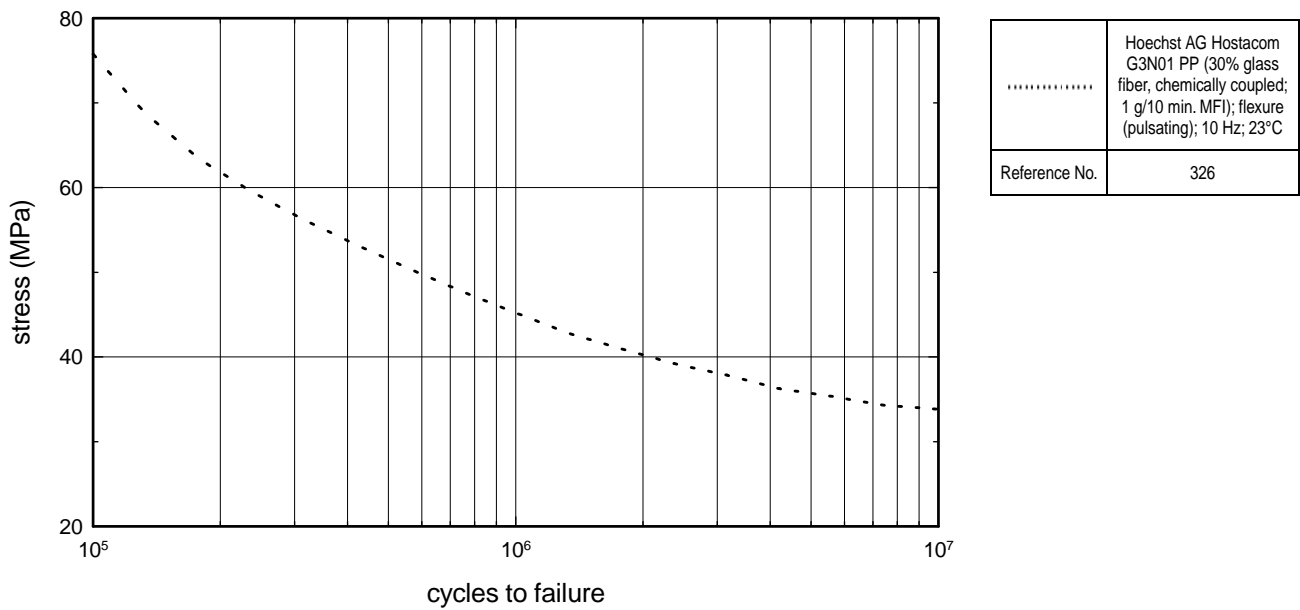
Graph 19.64 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostalen PPN 7790 GV2/30 Polypropylene.



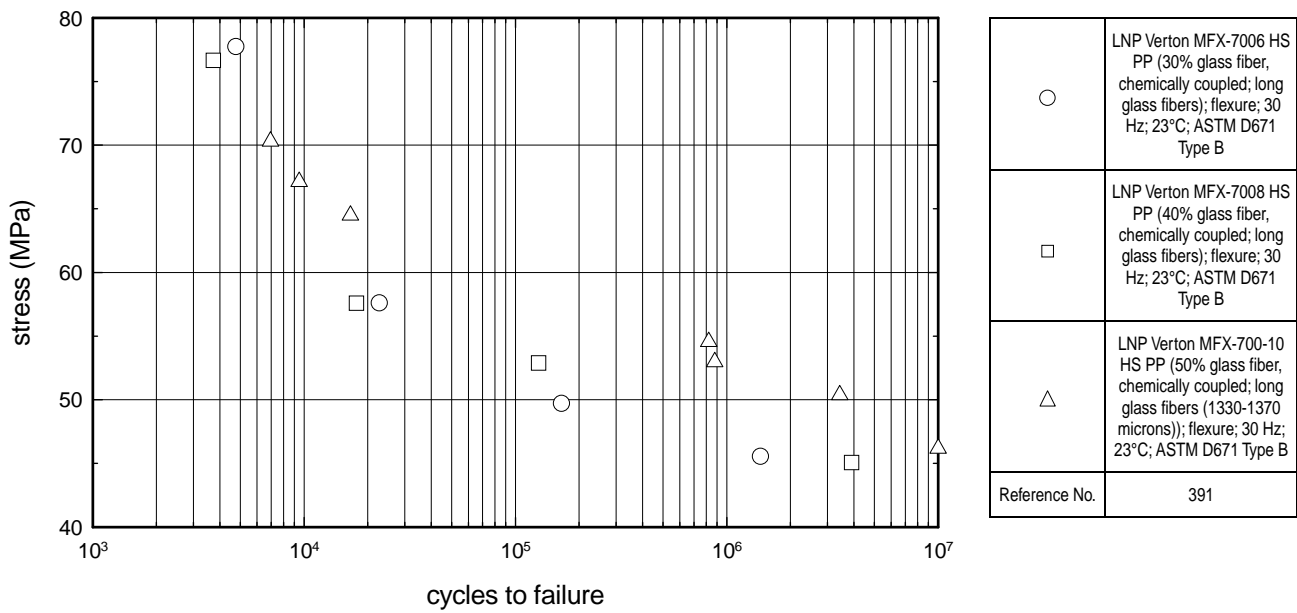
Graph 19.65 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostalen PPN 7790 GV2/30 Polypropylene.



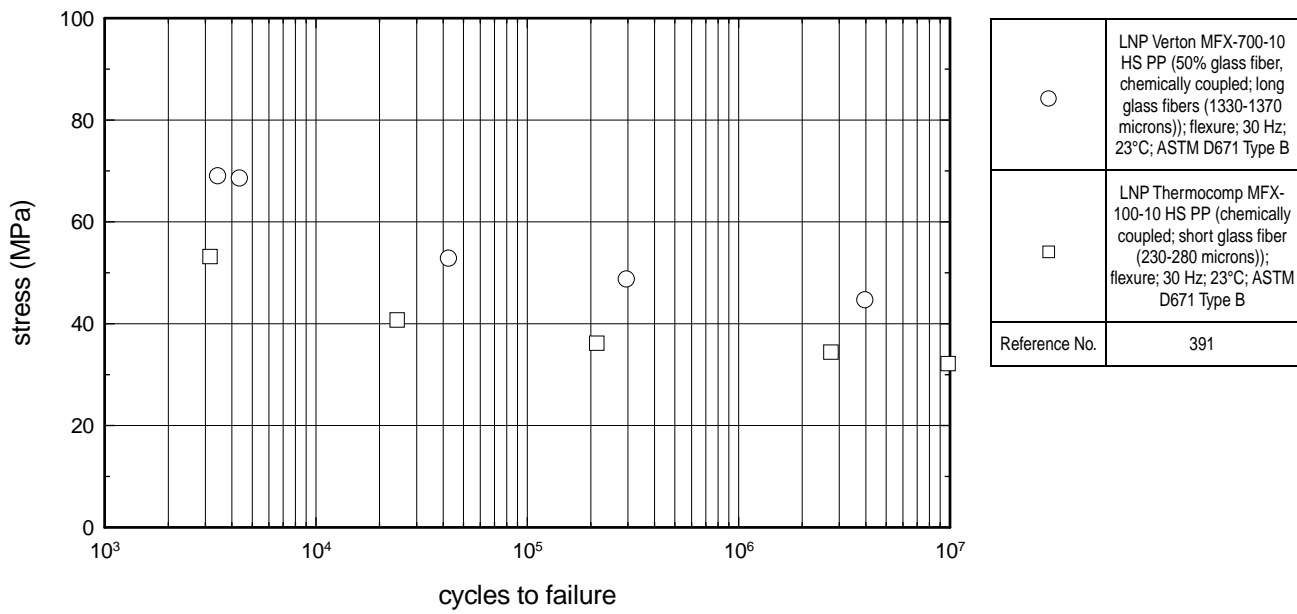
Graph 19.66 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostacom G3N01 Polypropylene.



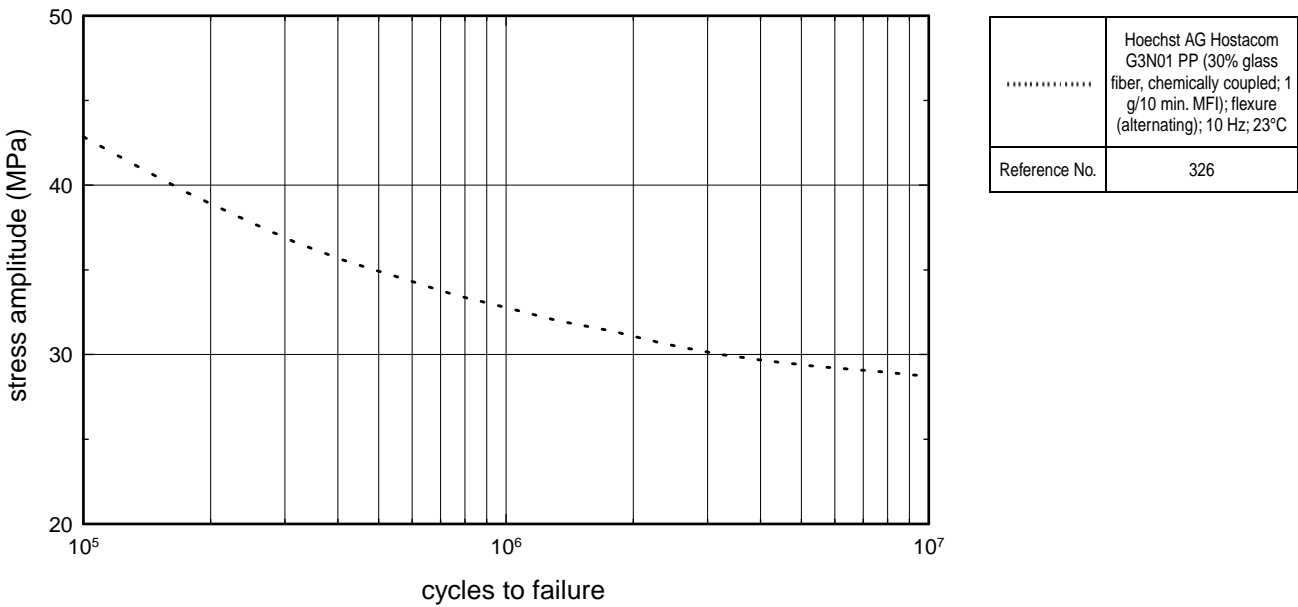
Graph 19.67 Fatigue Cycles to Failure vs. Stress in Flexure for Long Glass Fiber Reinforced Polypropylene.



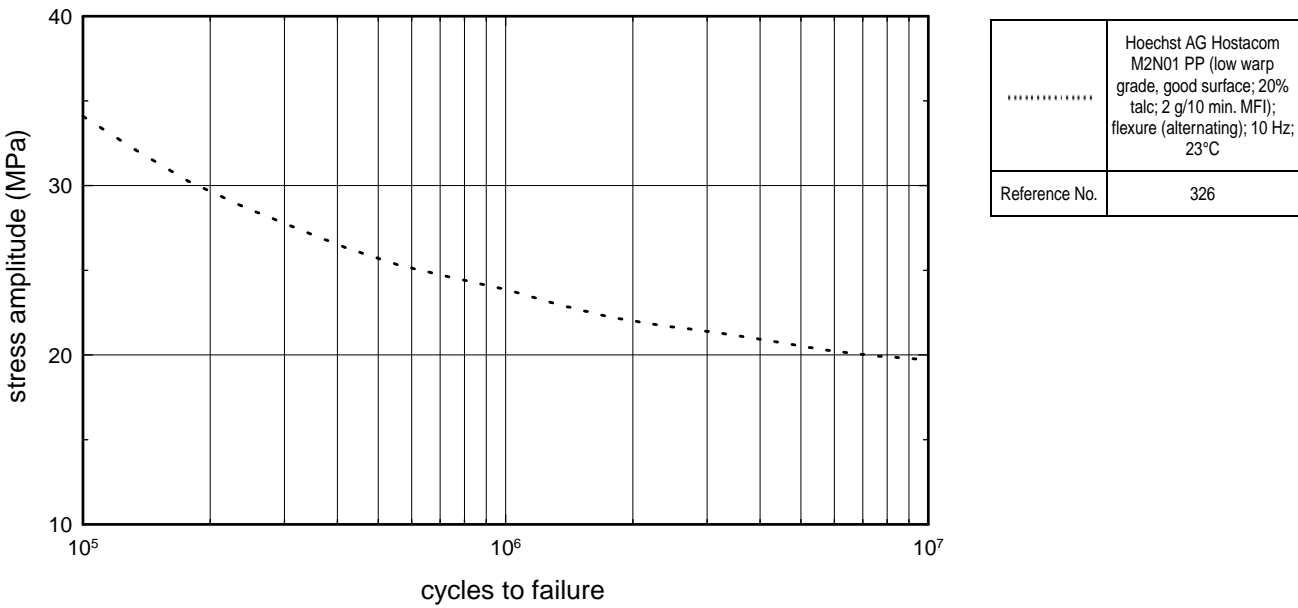
Graph 19.68 Fatigue Cycles to Failure vs. Stress in Flexure for Long and Short Glass Fiber Reinforced Polypropylene.



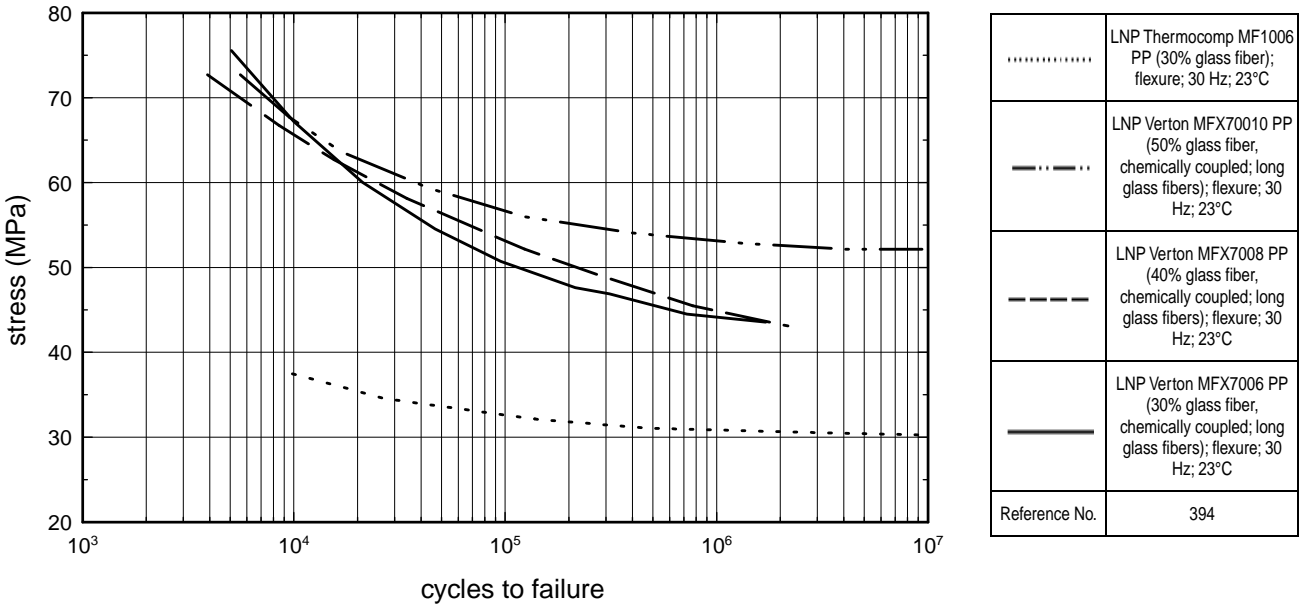
Graph 19.69 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostacom G3N01 Polypropylene.



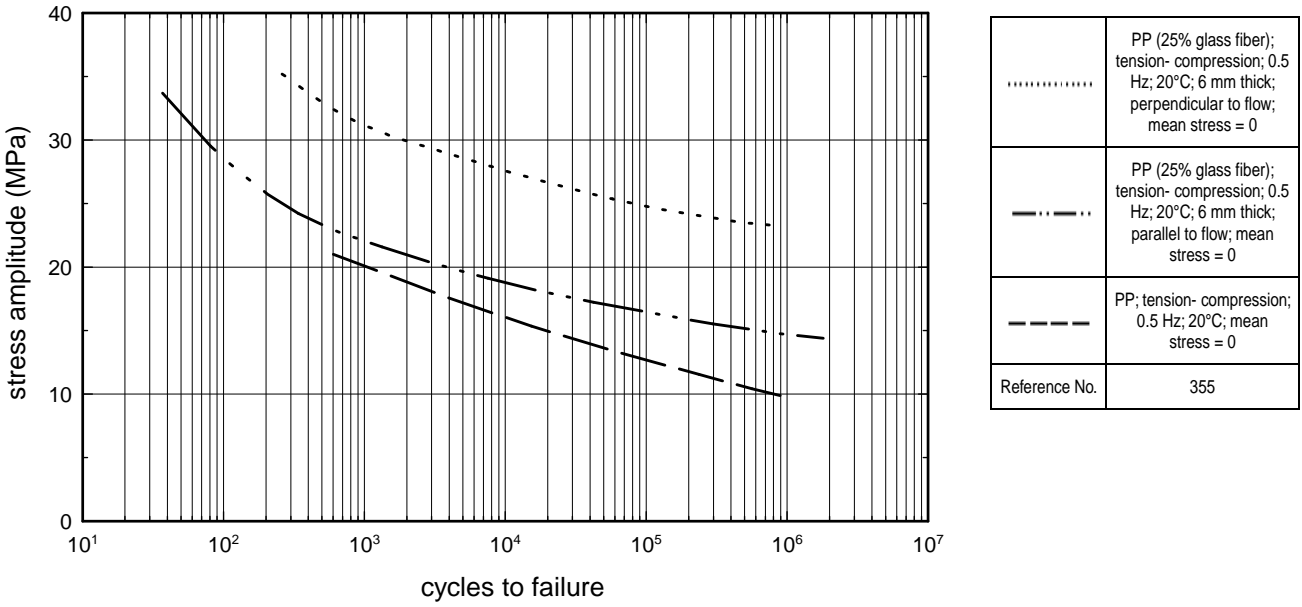
Graph 19.70 Fatigue Cycles to Failure vs. Stress in Flexure for Hoechst Hostacom M2N01 Polypropylene.



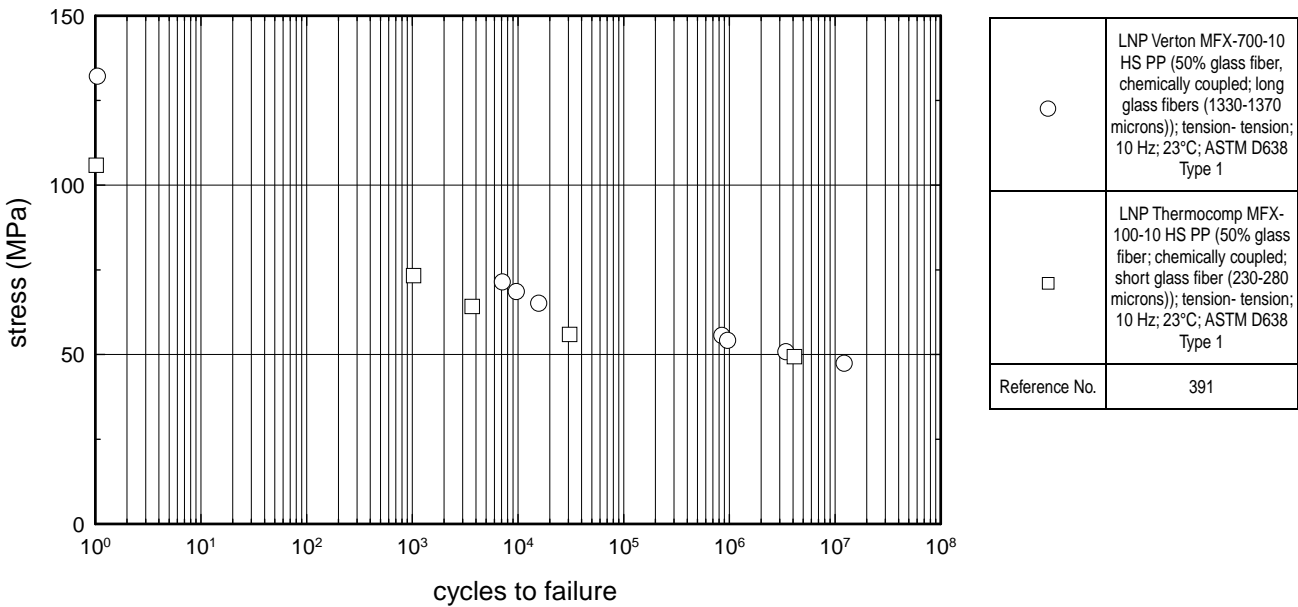
Graph 19.71 Fatigue Cycles to Failure vs. Stress in Flexure for Glass Fiber Reinforced LNP Polypropylene.



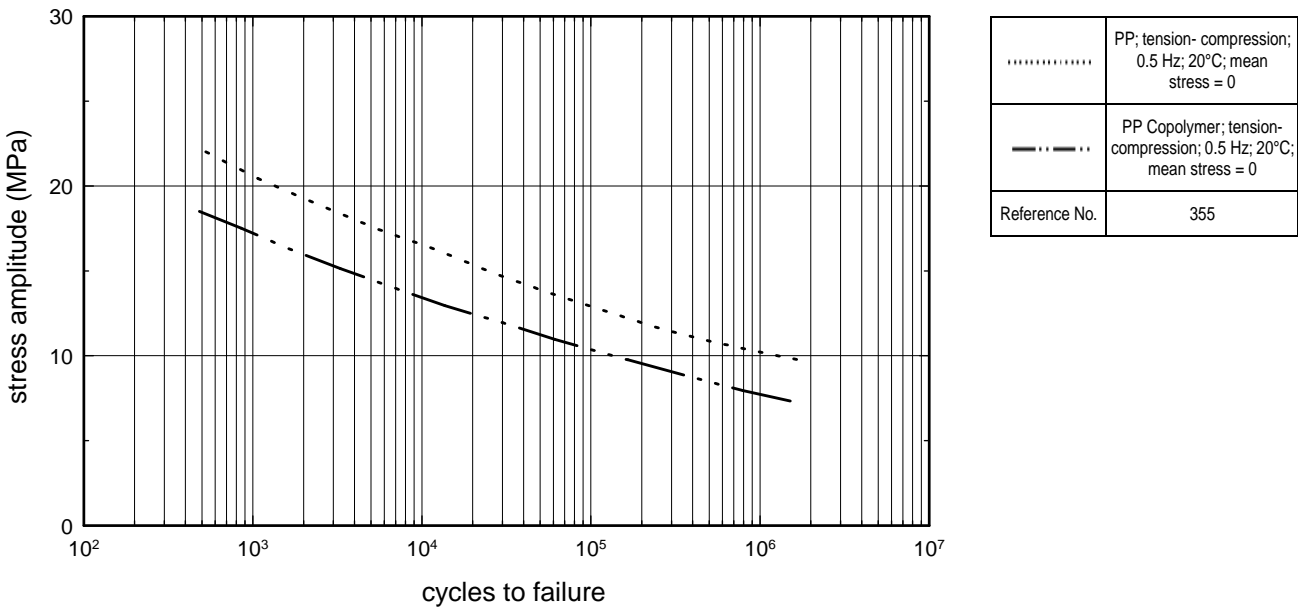
Graph 19.72 Fatigue Cycles to Failure vs. Stress in Tension for 25% Glass Fiber Reinforced Polypropylene.



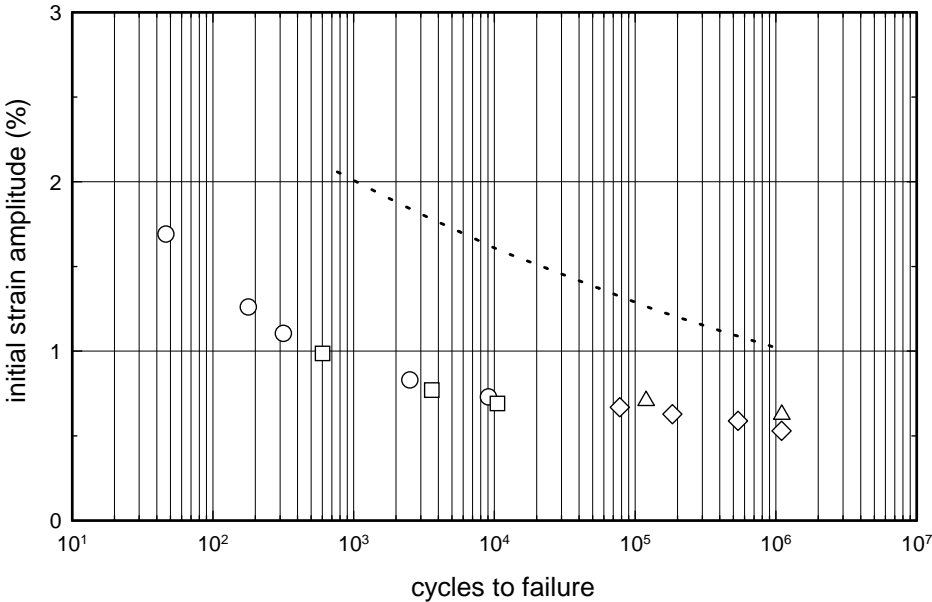
Graph 19.73 Fatigue Cycles to Failure vs. Stress in Tension for Long and Short Glass Reinforced Polypropylene.



Graph 19.74 Fatigue Cycles to Failure vs. Stress in Tension at Low Test Frequency for Polypropylene.

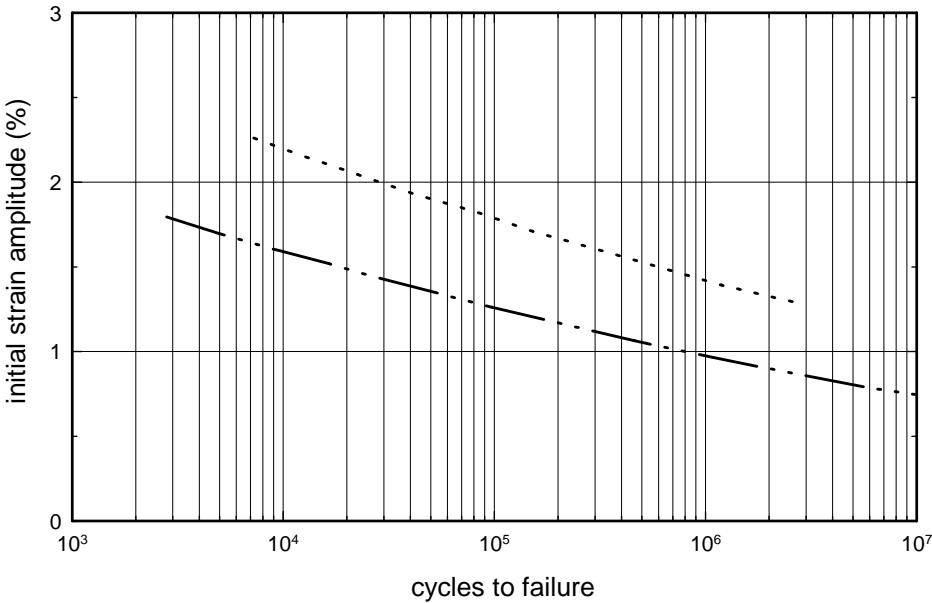


Graph 19.75 Fatigue Cycles to Failure vs. Initial Strain in Tension at Different Test Frequencies for Unreinforced and 25% Glass Fiber Reinforced Polypropylene.



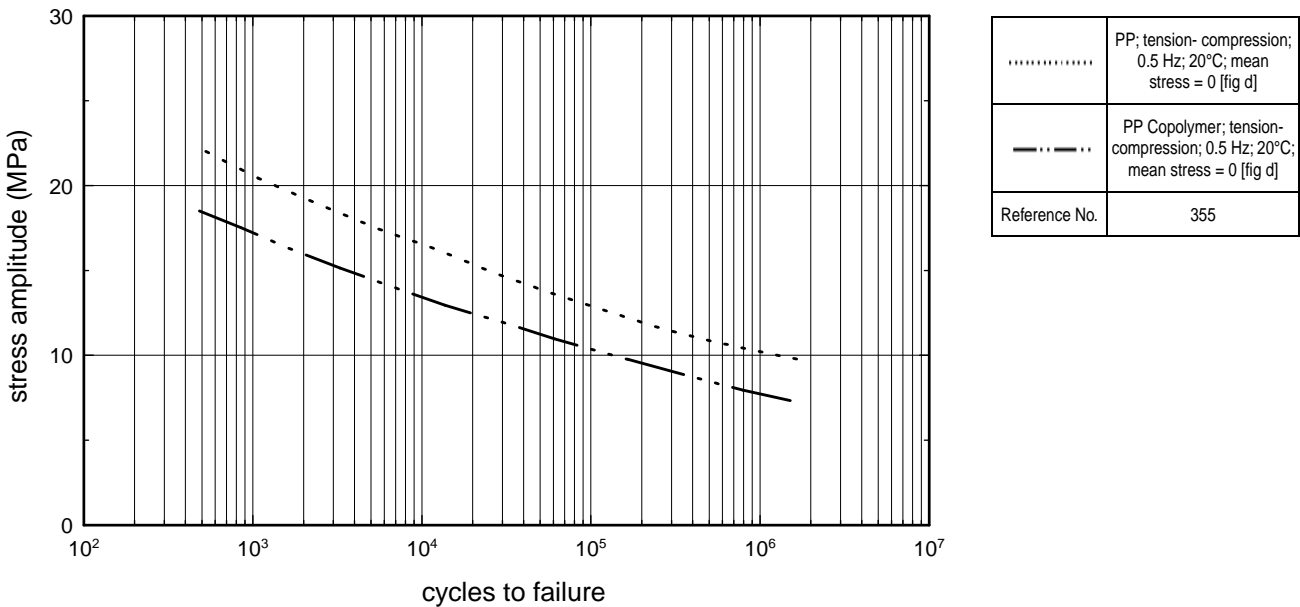
.....	PP; tension- compression; 0.5 Hz; 20°C; mean stress = 0
○	PP (25% glass fiber); tension- compression; 0.5 Hz; 20°C; 6 mm thick; parallel to flow; mean stress = 0
□	PP (25% glass fiber); tension- compression; 0.5 Hz; 20°C; 6 mm thick; perpendicular to flow; mean stress = 0
△	PP (25% glass fiber); tension- compression; 2.5 Hz; 20°C; 6 mm thick; perpendicular to flow; mean stress = 0
◇	PP (25% glass fiber); tension- compression; 2.5 Hz; 20°C; 6 mm thick; parallel to flow; mean stress = 0
Reference No.	355

Graph 19.76 Fatigue Cycles to Failure vs. Initial Strain in Tension at Low Test Frequency for Polypropylene.



.....	PP Copolymer; tension- compression; 0.5 Hz; 20°C; mean stress = 0 [fig d]
— · · · —	PP; tension- compression; 0.5 Hz; 20°C; mean stress = 0 [fig d]
Reference No.	355

Graph 19.77 Fatigue Cycles to Failure vs. Stress in Tension at Low Test Frequency for Polypropylene.



19.11 Permeability

This section is a compilation of permeability data for polypropylene. Information was coalesced from an extensive search of sources (i.e. conference proceedings, test laboratories, materials suppliers, monographs, trade and technical journals). The information is in the form of tables and graphs showing the data in as complete a form as it was presented in the source document.

For those who wish to delve beyond the data presented, source documentation is presented in detail. We also refer you to other publications available from PDL for more complete coverage of the subject of permeability. How a material performs in its end use environment is a critical consideration and the information here gives useful guidelines. However, this or any other information resource should not serve as a substitute for actual testing in determining the applicability of a particular part or material in a given end use environment.

Tables and graphs provide detailed test results in a clear, concise manner. Careful study of a table or graph will show how variations in material and test conditions influence a material’s physical characteristics. Each table or graph is designed to stand alone, be easy to interpret and provide all relevant and available details of test conditions and results. The information’s source is referenced to provide an opportunity for the user to find additional information. The source information might

also help to indicate any bias which might be associated with the data.

The permeation of gases and vapors through thin films is dependent on the molecular size, shape, wettability and soundness of the fabricated membrane. Since permeation in well made items is a molecular transport phenomenon, it is affected by orientation, degree of crystallinity and temperature. Attempts have been made to relate permeation rates through thin films to absorption of thicker films, sheets, pipe, etc. This has been generally unsuccessful. Thicker films and sheets represent an average set of properties obtainable from many thin films produced under a variety of conditions. To produce a thin film representative of this average is not practical.

19.11.1 Some Notes About The Information In This Section

This section contains data and information from disparate sources. In order to make the product most useful to end users, Plastics Design Library normalizes presentation of the information. Permeability data, for example, are presented in many different units (greater than 60) throughout the literature. In this section, permeability data have been normalized into two units — **cm³·mm/m²·day·atm** for permeability coefficient and **g·mm/m²·day** for vapor transmission rate.

Although substantial effort is exerted throughout the editorial process to maintain accuracy and consistency in unit conversion and presentation of information, possibility for error exists. Often these errors occur due to insufficient or inaccurate information in the source document. For this reason, values in the tables of permeability data are given in units as they appeared in the source document as well as in the converted (normalized) units.

19.11.2 Transport of Gases and Vapors in Barrier Materials

The most important properties of barrier materials are their transport properties. These properties are reviewed below.

19.11.3 Permeation Coefficient and Vapor Transmission Rate

The transport of gases and vapors in barrier materials such as polymeric films involves dissolving of the penetrant in the material, diffusion of dissolved penetrant through the material as a result of the concentration gradient and evaporation of the penetrant from the opposite surface of the material.

The transport of a penetrant in a barrier material can be described by Fick's first law stating that the volume (V) of a penetrant that penetrates a barrier wall is directly proportional to the area (A) of the wall, partial pressure differential (p) of the

penetrant and time (t); and inversely proportional to the wall thickness(s), if the wall is homogeneous in the direction of penetration. The coefficient P in the equation representing Fick's first law, $V = P \cdot (A \cdot p \cdot t)/s$, is the permeability coefficient.

Fick's first law applies only to permanent gases that obey Henry's law on proportionality of penetrant solubility in the barrier to the partial pressure of the penetrant. Therefore, the permeability coefficient can be measured under standard conditions only for permanent gases, i.e., gases that become liquid at pressures and temperatures far from normal (1 atm and 0°C, respectively). These gases include air, oxygen, argon and carbon dioxide.

The vapors of substances, such as water and acetone, that are liquid at pressures and temperatures close to normal do not obey Henry's law. Consequently, the permeability coefficient for the vapors is not proportional to the pressure differential in Fick's first law. To account for this fact, Fick's first law for vapors is expressed as $W = VTR \cdot (A \cdot t)/s$, where W is the weight of the penetrant and VTR is the vapor transmission rate. VTR is used to characterize the transport properties of barrier materials with respect to the vapors.

Convenient units of measurement for the permeability coefficient and the vapor transmission rate in the metric system are $(\text{cm}^3 \cdot \text{mm})/(\text{m}^2 \cdot \text{day} \cdot \text{atm})$ and $(\text{g} \cdot \text{mm})/(\text{m}^2 \cdot \text{day})$, respectively.

Table 19.2 Gas Permeability of Oxygen, Carbon Dioxide, Nitrogen and Helium Through Oriented Polypropylene Film.

Material Family	POLYPROPYLENE		
Product Form	FILM		
Features	oriented		
Reference Number	63	63	63

TEST CONDITIONS

Penetrant	oxygen	nitrogen	carbon dioxide
Temperature (°C)	25	25	25
Relative Humidity (%)	0	0	0

PERMEABILITY (SOURCE DOCUMENT UNITS)

Gas Permeability (cm ³ · mil/100 in ² · day)	174	42	528
Gas Permeability (cm ³ · 20μm ² · day · atm)	3400	730	9100

PERMEABILITY (NORMALIZED UNITS)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)	68.5	16.5	208
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Table 19.3 Oxygen Permeability at Different Temperatures and Water Vapor Transmission Through Oriented and Non-Oriented Polypropylene.

Material Family	POLYPROPYLENE			
Features	oriented	oriented	biaxially oriented	
Reference Number	264	264	264	264

TEST CONDITIONS

Penetrant	oxygen		water vapor	
Temperature (°C)	23	35	40	40
Relative Humidity (%)	0	0	90	90

PERMEABILITY (source document units)

Gas Permeability (cm ³ · mil/100 in ² · day)	163	203		
Gas Permeability (cm ³ · 25μm ² · day · atm)	2526	3146		
Vapor Transmission Rate (g · mil/100 in ² · day)			0.38	0.69
Vapor Transmission Rate (g · 25μm ² · day)			5.9	10.7

PERMEABILITY (normalized units)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)	64.2	80.0		
Vapor Transmission Rate (g · mm/m ² · day)			0.15	0.27

Table 19.4 Oxygen Permeability vs. Relative Humidity Through Biaxially Oriented Polypropylene Film.

Material Family	POLYPROPYLENE			
Product Form	FILM			
Features	biaxially oriented; PVDC coated			
Reference Number	265	265	265	265

TEST CONDITIONS

Penetrant	oxygen			
Temperature (°C)	20	20	20	20
Relative Humidity (%)	65	85	100	0

PERMEABILITY (source document units)

Gas Permeability (cm ³ · mil/100 in ² · day)	0.55	0.55	0.55	1.1
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PERMEABILITY (normalized units)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)	0.22	0.22	0.22	0.43
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Table 19.5 Water Vapor Transmission and Oxygen Permeability Through Polypropylene.

Material Family	POLYPROPYLENE			
Product Form	FILM			
Reference Number	101	101	296	296

TEST CONDITIONS

Penetrant	water vapor	oxygen	oxygen	water vapor
Temperature (°C)	37.8	23	22.8	37.8
Relative Humidity (%)	90		0	90
Test Method	ASTM D96	ASTM D1434	ASTM D1434	ASTM F1249

PERMEABILITY (source document units)

Gas Permeability (cm ³ · mil/100 in ² · day)		272	>250	
Vapor Transmission Rate (g · mil/100 in ² · day)	1.5			1
Vapor Transmission Rate (g · mm/ day/ m ²)	0.59			

PERMEABILITY (normalized units)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)		107	>99.7	
Vapor Transmission Rate (g · mm/m ² · day)	0.59			0.4

Table 19.6 Xylene and Oxygen Permeability Through Polypropylene.

Material Family	POLYPROPYLENE	
Reference Number	293	293

TEST CONDITIONS

Penetrant	xylene	oxygen
Temperature (°C)	60	23
Exposure Time (days)	14	
Relative Humidity (%)		75

PERMEABILITY (source document units)

Vapor Transmission Rate (g · mil/100 in ² · day)	2500	
Gas Permeability (cm ³ · mil/100 in ² · day)		200

PERMEABILITY (normalized units)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)		78.7
Vapor Transmission Rate (g · mm/m ² · day)	984	

Table 19.7 Water Vapor Transmission and Oxygen Permeability Through Coated and Uncoated Oriented Polypropylene Film.

Material Family	POLYPROPYLENE									
Product Form	FILM									
Features	oriented									
Reference Number	268	268	268	268	268	268	268	268	268	268

MATERIAL CHARACTERISTICS

Sample Thickness	0.02 mm	0.022 mm	0.02 mm	0.022 mm	0.02 mm	0.022 mm	0.02 mm	0.022 mm	0.02 mm	0.022 mm
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MATERIAL COMPOSITION

Note		PVDC coated		PVDC coated		PVDC coated		PVDC coated		PVDC coated
------	--	-------------	--	-------------	--	-------------	--	-------------	--	-------------

TEST CONDITIONS

Penetrant	water vapor		oxygen							
Temperature (°C)	40	40	35	35	20	20	20	20	20	20
Relative Humidity (%)	90	90	0	0	65	65	85	85	100	100
Test Method	JIS Z0208	JIS Z0208	JIS Z1707	JIS Z1707	ASTM D3985	ASTM D3985	ASTM D3985	ASTM D3985	ASTM D3985	ASTM D3985

PERMEABILITY (source document units)

Vapor Transmission Rate (g · mil/100 in ² · day)	<1	<1								
Gas Permeability (cm ³ · mil/100 in ² · day)			226	1.23	135	0.65	135	0.65	135	0.65

PERMEABILITY (normalized units)

Permeability Coefficient (cm ³ · mm/m ² · day · atm)			89.0	0.48	53.2	0.26	53.2	0.26	53.2	0.26
Vapor Transmission Rate (g · mm/m ² · day)	<0.39	<0.39								

Table 19.8 Organic Solvents Permeability Through Oriented Polypropylene Film.

Material Family	POLYPROPYLENE			
Product Form	FILM			
Features	oriented	oriented	oriented	oriented
Reference Number	266	266	266	266

MATERIAL CHARACTERISTICS

Sample Thickness	0.02 mm	0.02 mm	0.02 mm	0.02 mm
------------------	---------	---------	---------	---------

TEST CONDITIONS

Penetrant	chloroform	xylene	methyl ethyl ketone	kerosine
Temperature (°C)	20	20	20	20
Relative Humidity (%)	65	65	65	65

PERMEABILITY (source document units)

Vapor Transmission Rate (g/day · 100 in ²)	241.3	22.58	0.77	3.42
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PERMEABILITY (normalized units)

Vapor Transmission Rate (g · mm/m ² · day)	74.8	7	0.24	1.06
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Table 19.9 d-Limonene (flavor component) Permeability Through Polypropylene.

Material Family	POLYPROPYLENE
Product Form	FILM
Reference Number	255

TEST CONDITIONS

Penetrant	d-limonene
Temperature (°C)	25
Relative Humidity (%)	dry

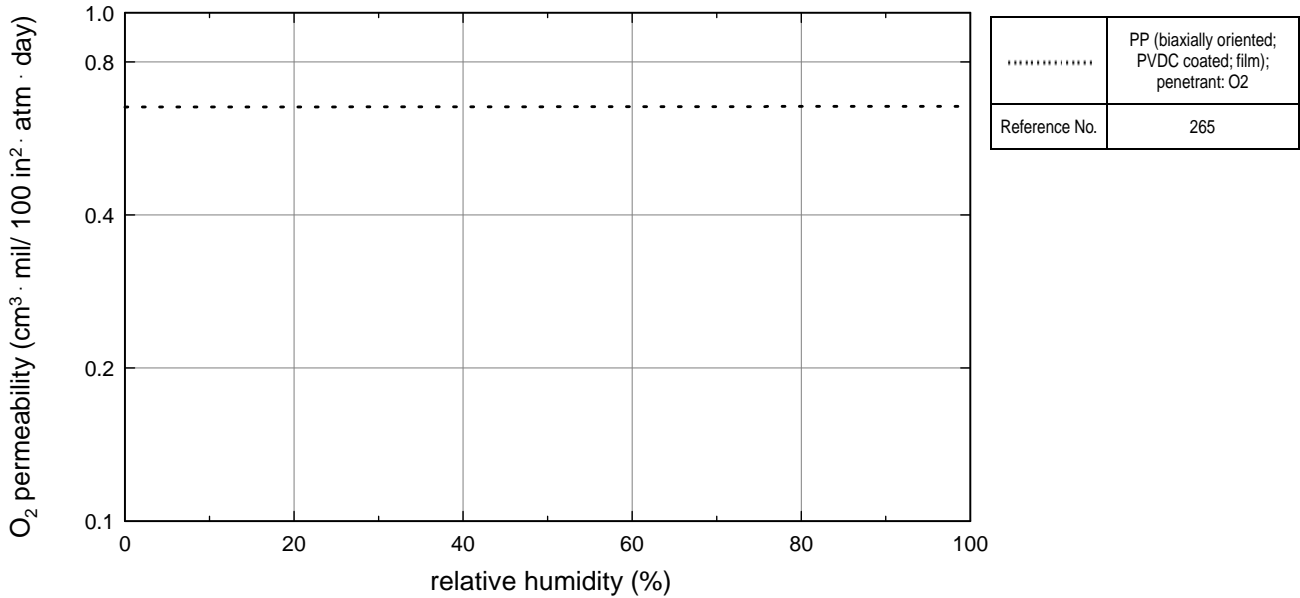
PERMEABILITY (source document units)

Vapor Transmission (10 ⁻²⁰ kg · m/m ² · sec · Pa)	101,800
--	---------

PERMEABILITY (normalized units)

Vapor Transmission Rate (g · mm/m ² · day)	8.9
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Graph 19.78 Oxygen Permeability vs. Relative Humidity through Polypropylene.



19.12 Effect of Weather and UV Light

This section is a compilation of data on how weathering and UV light affect the properties and characteristics of polypropylene. Information on the effects of weathering on polypropylene is not readily available. This section presents a compilation of information resulting from an extensive search of wide ranging sources (i.e. conference proceedings, test laboratories, materials suppliers, monographs, trade and technical journals). The information is in the form of tables and graphs showing the data in as complete a form as it was presented in the source document.

For those who wish to delve beyond the data presented, source documentation is presented in detail. We also refer you to other publications available from PDL for more complete coverage of the subject of weathering. How a material performs in its end use environment is a critical consideration and the information here gives useful guidelines. However, this or any other information resource should not serve as a substitute for actual testing in determining the applicability of a particular part or material in a given end use environment.

Tables and graphs provide detailed test results in a clear, concise manner. Careful study of a table or graph will show how variations in material, exposure conditions and test conditions influence a material's physical characteristics. Each table or graph is designed to stand alone, be easy to interpret and provide all relevant and available details

of test conditions and results. The information's source is referenced to provide an opportunity for the user to find additional information. The source information might also help to indicate any bias which might be associated with the data.

19.12.1 Weather Defined

Webster defines weathering as “Noun. Action of the elements in altering the color, texture, composition, or form of exposed objects. Weather: to expose to air; to season, dry, pulverize, discolor, etc. by exposure to air.” In essence, weathering is the natural tendency of materials to return — corrode, oxidize, chalk, permeate, delaminate, depolymerize, flex crack, etc. — to their elemental forms.

The sun's powerful ultraviolet rays combined with the effects of heat and moisture cause millions of dollars of damage every year to exposed materials. Ultraviolet light as sunlight, water as rain or dew, temperature and their combined effects are substantial stresses. Degradation also occurs from localized stresses such as microbiologic attack, air pollution and salt water.

19.12.2 Variations In Natural Weathering

Weather is variable — regional variations, local variations, seasonal variations, yearly variations, etc. Exposure to a tropical climate such as Florida can easily be twice as severe as exposure in northerly regions. This is due to the increase in ultra-

violet radiation caused by the higher average sun angle and its exceptionally moist climate. On the other hand, Arizona may offer an increased ultraviolet radiation degradation, but it has a much lower rate of deterioration due to wetness.

Seasonal variations such as higher temperature and increased ultraviolet radiation (due to a higher sun angle in summer) can cause summer exposure to be 2 to 7 times as severe as winter exposure in the same place. Variations in weather can change from year to year making one year twice as severe as the last. Natural, accelerated, and artificial testing attempts to recreate weathering and its variability, usually under conditions more severe than normally encountered.

19.12.3 Testing For Weatherability

Man attempts to prevent deterioration and discoloration due to weathering by examining the nature of the physics and chemistry at the interface of pigments, fillers and polymers and then creating the anti-corrosion, anti-oxidant, additive, or coating technology to extend the useful life of natural and synthetic products. However, the only way to reliably predict their durability is through comprehensive testing.

The primary purpose served by examining data on weathering of materials is to predict any potential changes of both physical properties and appearance of a part made from those materials. Data on the aging behavior of plastics are acquired

through accelerated tests and/or actual weather exposure. These tests serve as a means for comparison of materials and can also be exploited to determine the ability of the material to serve its function when formed into a part and used in a particular environment. Comparisons between materials are made by measuring the retention of properties (e.g. impact strength, gloss, tensile strength, yellowness index, etc.) significant to the application as a function of exposure time. The demand for new products has shortened the time available for determining the durability of a particular material. Therefore, accelerated weathering is increasingly used in an attempt to predict the long term environmental effects in less time than the real time working life expectancy.

19.12.4 Effect of White Pigments on Weatherability

PP (material composition: 40% Microcal C110S (calcium carbonate — ECC Int.))

Poor quality, impure calcium carbonate filler can adversely affect weatherability. Therefore, generally only fine, relatively pure products are used. Microcal C110S performs favorably on the weathering of polypropylene with a fine competitive limestone product in respect to the change in key properties after 18 weeks exposure in a QUV weatherometer.

Reference: *Microcal Spa C110S For Polypropylene*, supplier technical report (APP033 PI) — ECC International, 1993.

Table 19.10 Effect of Antioxidants on Outdoor Weathering in Florida and Puerto Rico of Polypropylene.

Material Family	POLYPROPYLENE										
Product Form	200/16 DENIER NATURAL MULTIFILAMENT SAMPLES										
Reference Number	207	207	207	207	207	207	207	207	207	207	207

MATERIAL COMPOSITION

calcium stearate	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr
Good-rite 3114 (antioxidant — American Cyanamid)	0.1 phr	0.1 phr	0.1 phr								
Irganox 1010 (antioxidant — Ciba Geigy)							0.08 phr	0.08 phr	0.08 phr	0.08 phr	0.08 phr
Irganox 1076 (antioxidant — Ciba Geigy)				0.1 phr	0.1 phr	0.1 phr					
TBPP (antioxidant)										0.1 phr	0.3 phr
Ultrinox 626 (antioxidant — General Electric)		0.15 phr			0.15 phr			0.1 phr	0.3 phr		
Weston 619 (antioxidant — General Electric)			0.15 phr			0.15 phr					

EXPOSURE CONDITIONS

Exposure Type	outdoor weathering						outdoor weathering				
Exposure Location							Florida				
Exposure Country	Puerto Rico						USA				
Exposure Note	total radiation is radiation required to reach 50% retention of initial tensile strength						total radiation is radiation required to reach 50% retention of initial tensile strength				
Total Radiation (Langleys)	43,000	65,000	72,000	43,000	69,000	54,000	24,000	39,000	47,000	26,000	24,000

PROPERTIES RETAINED (%)

Tensile Strength	50	50	50	50	50	50	50	50	50	50	50
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Table 19.11 Outdoor Weathering in California and Pennsylvania of Glass Reinforced Polypropylene.

Material Family	POLYPROPYLENE							
Material Supplier	LNP ENGINEERING PLASTICS							
Reference Number	215	215	215	215	215	215	215	215

MATERIAL COMPOSITION

carbon black	1%	1%	1%	1%	1%	1%	1%	1%
glass fiber reinforcement	30%	30%	30%	30%	30%	30%	30%	30%

EXPOSURE CONDITIONS

Exposure Type	outdoor weathering				outdoor weathering			
Exposure Location	Los Angeles, California	Los Angeles, California	Los Angeles, California	Los Angeles, California	Philadelphia, Pennsylvania	Philadelphia, Pennsylvania	Philadelphia, Pennsylvania	Philadelphia, Pennsylvania
Exposure Country	USA	USA	USA	USA	USA	USA	USA	USA
Exposure Test Method	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435
Exposure Time (days)	91	182	365	730	91	182	365	730

PROPERTIES RETAINED (%)

Tensile Strength	99	100	105	105	93	94	107	106
Notched Izod Impact Strength	100	100			91	100		
Unnotched Izod Impact Strength	108	104			121	85.7		

Table 19.12 Effect of Stabilizers and Antioxidants on Outdoor Weathering in Puerto Rico of Polypropylene.

Material Family	POLYPROPYLENE										
Product Form	200/16 DENIER NATURAL MULTIFILAMENT SAMPLES										
Reference Number	207	207	207	207	207	207	207	207	207	207	207

MATERIAL COMPOSITION

calcium stearate	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr	0.05 phr
P-EPQ (antioxidant)						0.15 phr					
Good-rite 3114 (antioxidant — American Cyanamid)	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr	0.1 phr
Ultrinox 626 (antioxidant — General Electric)			0.15 phr						0.1 phr		0.1 phr
Weston TNPP (antioxidant — General Electric)					0.15 phr						
Weston 619 (antioxidant — General Electric)				0.15 phr							
Cyasorb UV 531 (UV absorber — American Cyanamid)	0.15 phr	0.3 phr	0.15 phr	0.15 phr	0.15 phr	0.15 phr					
Tinuvin 144 (UV stabilizer — Ciba Geigy)										0.4 phr	0.3 phr
Tinuvin 770 (hindered amine light stabilizer — Ciba Geigy)							0.3 phr	0.4 phr	0.3 phr		

EXPOSURE CONDITIONS

Exposure Type	outdoor weathering						outdoor weathering				
Exposure Country	Puerto Rico						Puerto Rico				
Exposure Note	total radiation is radiation required to reach 50% retention of initial tensile strength						total radiation is radiation required to reach 70% retention of initial tensile strength, experiment terminated due to lack of further test samples				
Total Radiation (Langley's)	48,000	59,000	93,000	113,000	55,000	59,000	176,000	>191,000	>191,000	150,000	150,000

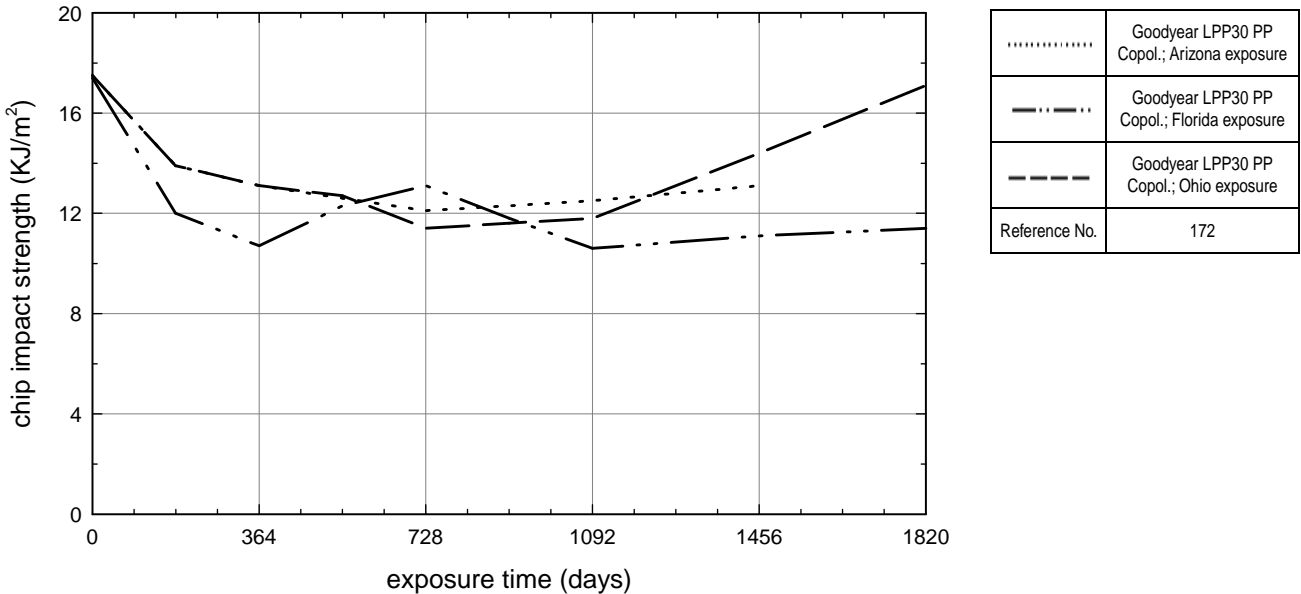
PROPERTIES RETAINED (%)

Tensile Strength	50	50	50	50	50	50	70	70	70	70	70
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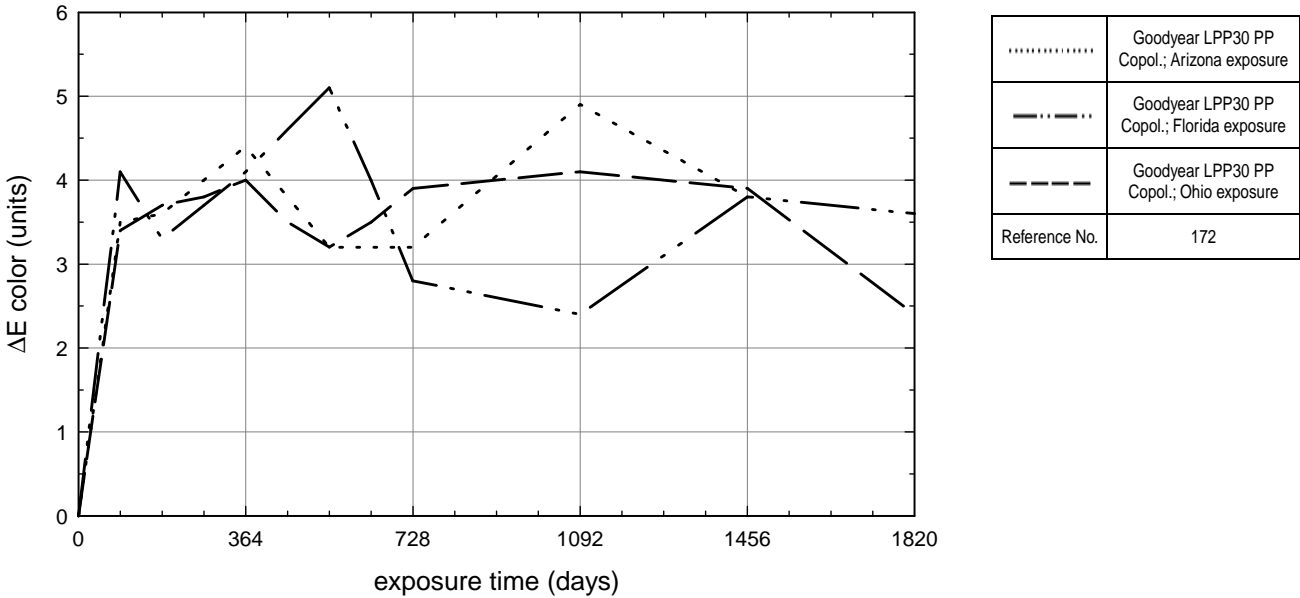
Table 19.13 Effect of ECC International Microcal Calcium Carbonate on Accelerated Weathering in QUV of Polypropylene.

Material Family	POLYPROPYLENE	
Reference Number	159	159
MATERIAL COMPOSITION		
calcium carbonate (limestone)		40%
Microcal C110S (calcium carbonate — ECC International)	40%	
EXPOSURE CONDITIONS		
Exposure Type	accelerated weathering	accelerated weathering
Exposure Apparatus	QUV	QUV
Exposure Apparatus Note	B lamps	B lamps
Exposure Time (days)	126	126
Exposure Note	4 hours UV, 4 hours moisture	4 hours UV, 4 hours moisture
SURFACE AND APPEARANCE		
Δa Color Change (%)	-0.26	-0.2
Δb Color Change (%)	-0.24	0.15
ΔL Color Change (%)	0.38	0.55
Gloss @ 60° Change (%)	-0.3	-0.8

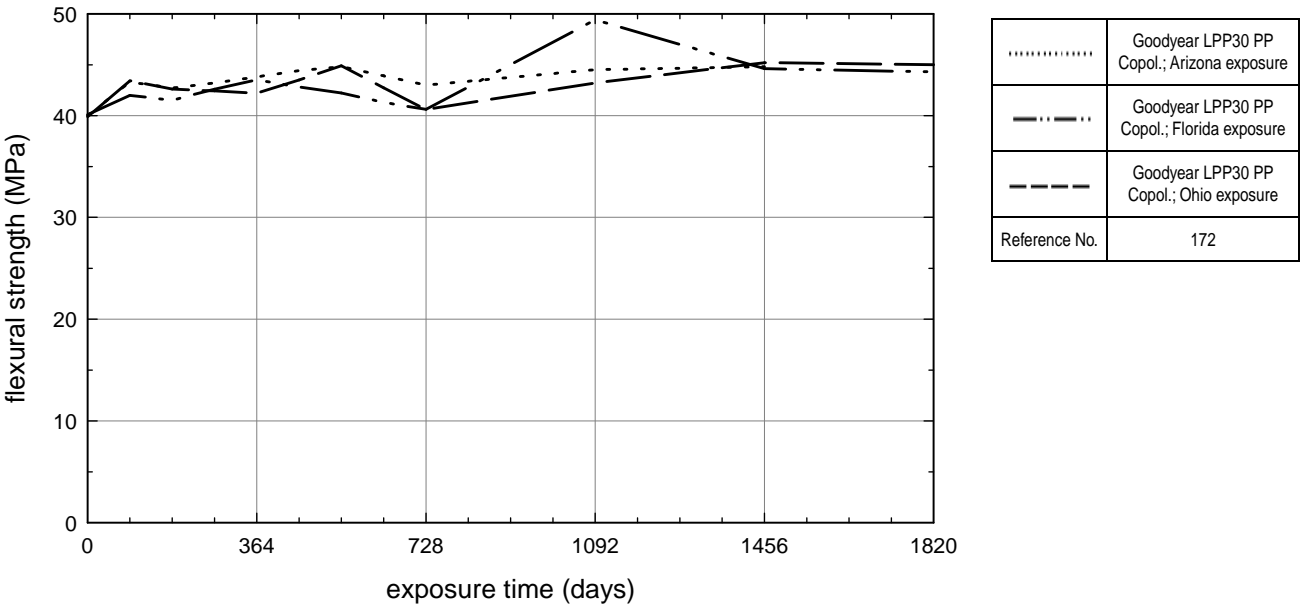
Graph 19.79 Outdoor Exposure Time vs. Chip Impact Strength of Polypropylene Copolymer



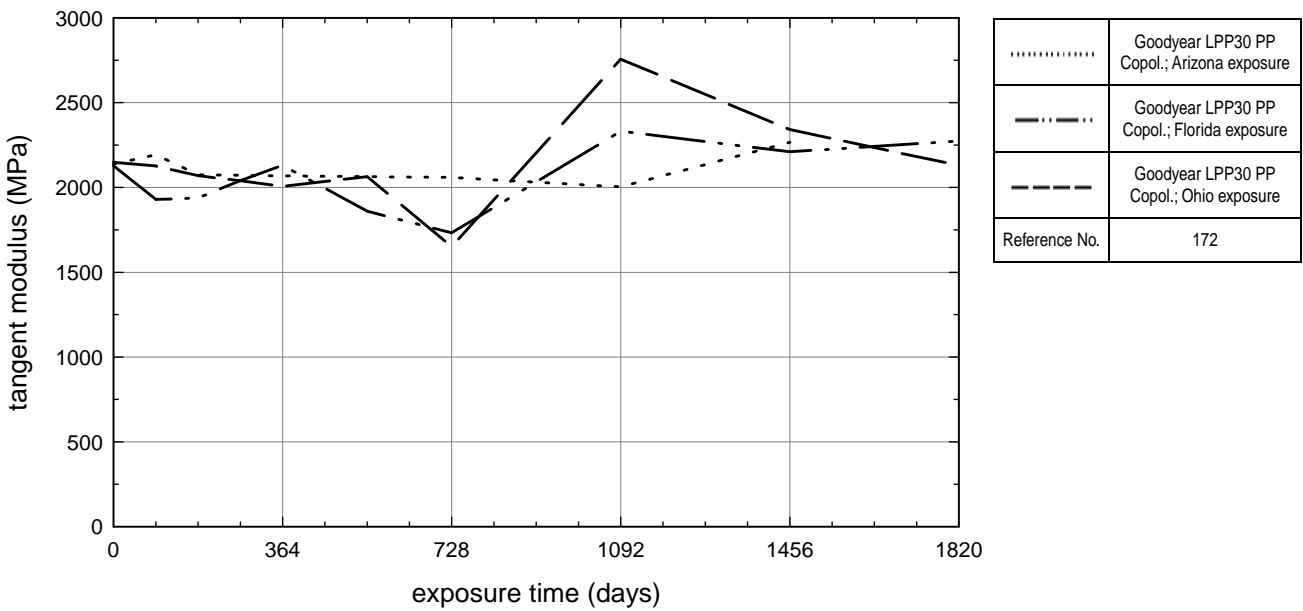
Graph 19.80 Outdoor Exposure Time vs. Delta E Color Change of Polypropylene Copolymer



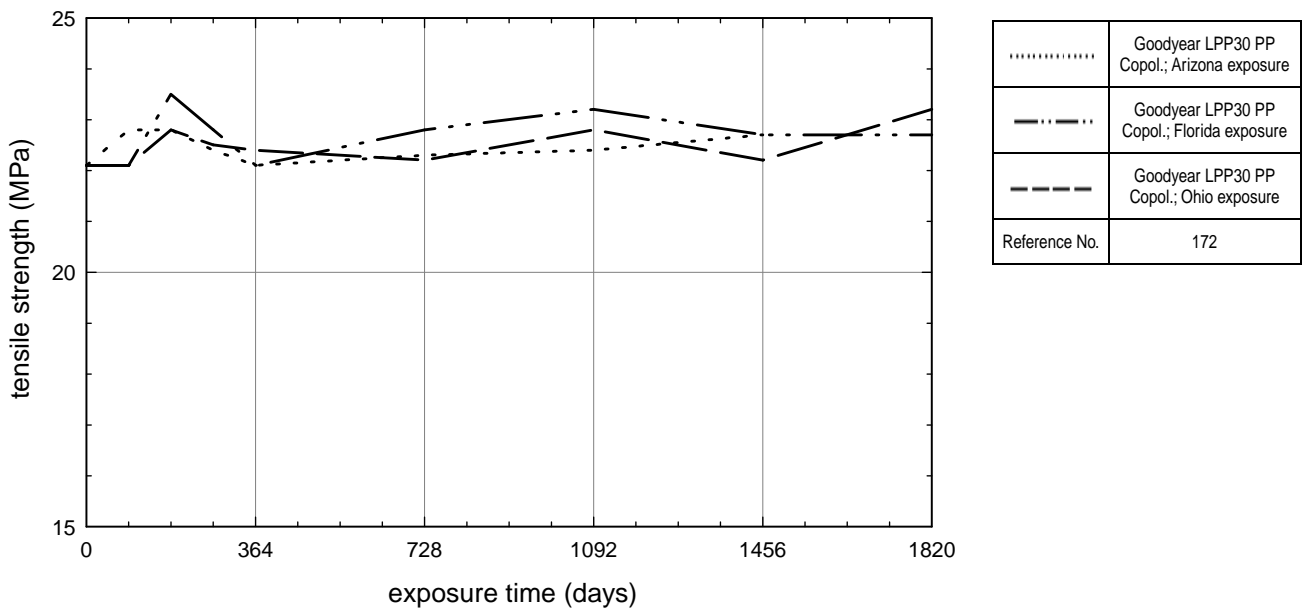
Graph 19.81 Outdoor Exposure Time vs. Flexural Strength of Polypropylene Copolymer



Graph 19.82 Outdoor Exposure Time vs. Tangent Modulus of Polypropylene Copolymer



Graph 19.83 Outdoor Exposure Time vs. Tensile Strength of Polypropylene Copolymer



19.13 Effect of Sterilization Methods

This section presents a compilation of how sterilization methods, and their assistant media, affect the properties and characteristics of polypropylene. The primary focus of sterilization is killing microorganisms. But the impact of sterilization methods extends beyond the cleaning of medical devices. For instance, irradiation, a widely used sterilization method, is also useful in modifying the physical properties of polymer materials to improve performance.

Four common types of sterilization are in use today: gas — ethylene oxide (EtO), steam autoclave, irradiation — gamma, electron beam, and beta radiation, and dry heat. Cold sterilization and disinfectants are also covered.

19.13.1 Ethylene Oxide

Ethylene Oxide, a dominant sterilization technique is declining in use due to the following:

- Physical property changes in polymers due to reactivity of the gas.
- Length of degassing time, product aeration and elimination of gas toxic residues.
- Absorption and adsorption of the gas, leaving residues and damaging the optical properties of the polymer.
- The Environmental Protection Agency has found EtO to be mutagenic and has initiated steps to restrict its use.
- Operator safety

Residual levels of EtO and related gas sterilants should fall within FDA guidelines, as follows:

Gas	Blood/Cardiac Devices and Implants	Topical Medical Devices
Ethylene Oxide	25 ppm	250 ppm
Ethylene Chlorohydrin	25 ppm	250 ppm
Ethylene Glycol	250 ppm	5000 ppm

Nevertheless EtO is the least aggressive form of sterilization for many materials. And the replacement of the most common EtO carrier gas — CFC-12 (Freon) — with non-ozone depleting alternatives, such as carbon dioxide and chlorotetrafluoroethane — HCFC-124, will cause EtO to remain a viable choice for many users of sterilization services.

19.13.2 Irradiation

Radiation sterilization can be accomplished using one of three forms of radiation: gamma, electron beam, or beta. Because repeated irradiation is equivalent to on going aging treatments, irradiation techniques have been successful for disposable articles, where only one dose is required. Polymers can also be modified, using irradiation, to improve physical properties and performance. Not all polymers will benefit and, in fact, many will degrade. Two factors predominate the change in physical properties; first, chain scission of the polymer molecule resulting in reduced molecular weight; and second, crosslinking of the polymer molecules resulting in the formation of large three dimensional matrices. These changes occur at the same time, and the predominance of one or the other, dependent on the polymer irradiated and radiation dose, will determine the outcome.

Those requiring radiation sterilization services or irradiation for polymer modification are increasingly looking to contract providers. This is a result of the ongoing cost and environmental pressures associated with EtO, coupled with the substantial capital required to construct an irradiation facility. The trend towards outsourcing should cause manufacturers to be more circumspect in their specification of materials and sterilization procedures since they give up direct control of this important function. For example, those using contract irradiation services should specify the minimum and maximum dose. All irradiation will result in the product getting a range of exposure. For gamma irradiation the range will typically be from 1.1 to 1.4 times the minimum dose; for electron beam the range is greater. If a minimum dose of 2.5 Mrads (25 kGy) is specified, the maximum dose may range from 2.75 Mrads (27.5 kGy) to 3.5 Mrads (37.5 kGy). The range in dosage absorbed results from a combination of packaging, part density and differences at irradiation facilities.

Gamma radiation is the most widely used sterilization method after EtO and the fastest growing of all sterilization methods. Gamma irradiation involves the bombardment of photons from a source such as Cobalt 60. It is characterized by deep penetration and low dose rates. Its high energy renders it capable of breaking any chemical bond present in a molecule, making it a good method for sterilizing devices composed of multiple resins. Gamma can penetrate large bulky objects. Prepackaged articles may therefore be ster-

ilized, as packaging materials like cellophane, cellulose acetate, polyethylene, nylon, and even metal can be penetrated. Gamma is considered to have five times the penetration capability, as compared to electron beam irradiation.

Electron beam irradiation is bombardment of high energy electrons. In this method, sterilization is quick but with limited penetration. Beta radiation (electrons generated from a linear accelerator) has seen increasing use in Europe and test results are presented. Its use is limited in much the same way as electron beam due to limited penetration.

19.13.3 Steam

Steam autoclave is a method by which a device is exposed to live steam in a pressurized chamber known as an autoclave. For non-critical applications, autoclaving is an acceptable method of sterilization. Types of autoclave sterilization include prevacuum, usually performed at 132°C (270°F), and gravity displacement cycle at 121°C (250°F). As condensation in an autoclave can cause impurities, steam is usually fed from a central boiler system where low concentrations of rust inhibiting feed water additives often are used to act as acid scavengers in steam condensate. Medical devices may be exposed to a variety of potentially aggressive agents such as soaps, lubricants, common disinfectants and rust inhibiting feed water additives. Generally a single exposure to these agents will not cause a change in properties. However, residue from these reagents left on a part during sterilization drying cycles can increase the chemical's concentration, causing the substance to react with the resin over time.

19.13.4 Dry Heat

Dry heat sterilization is generally accomplished by subjection to high heat (165 °C to 170 °C) for 2 to 3 hours in ovens.

19.13.5 Radiation Resistance

Quantum: Petrothene Waste containers and bags extruded from polypropylene can be sterilized by radiation.

Reference: *Performance Polyolefins For The Healthcare Market*, supplier marketing literature (6615/591) — Quantum Chemical Corporation, 1991.

19.13.6 Gamma Radiation Resistance

Himont: Profax PF511 (features: gamma radiation stabilized, high flow)

Pro-fax PF511 resists embrittlement after 5 Mrads of gamma radiation.

Reference: Pro-fax PF511 High-Flow, Radiation-Resistant Polypropylene, supplier marketing literature — Himont, 1989.

Eastman: Tenite P7673-960A (melt flow rate: 18 g/10 min.; features: gamma radiation stabilized); **Tenite P7673-984A** (melt flow rate: 18 g/10 min.; features: gamma radiation stabilized); **Tenite** (features: general purpose grade)

When a normally stabilized polypropylene is subjected to gamma radiation for sterilization purposes, two major changes may take place. A yellow color may develop due primarily to a chemical change in certain stabilizers that is initiated by radiation. Radiation will alter the chemical structure in such a way that it becomes more susceptible to oxidation. Therefore, the time required for an irradiated part to discolor or embrittle may be very short. Based on correlations between room temperature aging and accelerated aging at 43°C, the estimated shelf life of these materials after sterilization with gamma rays is three to five years. It appears from these correlations that aging for 30 days at 43°C is approximately equivalent to aging one year at 23°C. The materials studied were irradiated to 2.5 Mrads at an average dose rate of 0.1 Mrad/hour. Since a low rate is more harmful than a high dose rate, the data were generated under the worst conditions likely to be encountered.

The two most significant tests to monitor the effect of radiation on polypropylene are elongation at break and color. Samples were tested prior to irradiation (2.5 Mrads), immediately after irradiation but prior to oven aging, and at 30 day intervals (up to 180 days) after oven aging at 43°C. Elongation decreases to a certain level upon irradiation and apparently holds close to that level with time. Polypropylene with radiation stabilizers has high elongation after irradiation, indicating physical properties are maintained at a desirable level. Elongation of most regular polypropylenes drops to an unacceptable level after irradiation. The resulting embrittlement would make regular polypropylene unacceptable for producing medical devices that require radiation sterilization.

A color change due to radiation sterilization will be noticeable immediately after sterilization. This yellowness may decrease slightly during the early stages of aging. However, unless the material is properly stabilized, color will increase again with continued aging. Tensile yield strength and

notched Izod do not appear to change significantly after irradiation.

Reference: Tenite Polypropylene And Tenite Polyallomer Materials For Radiation Sterilization, supplier technical report (MB-93) — Eastman Plastics, 1985.

Exxon: Polypropylene (composition: novel polypropylene copolymer with a hindered amine light stabilizer, no nucleator; features: gamma radiation stabilized, transparent, developmental material); **Polypropylene** (composition: polypropylene homopolymer with a hindered amine light stabilizer, no nucleator; features: gamma radiation stabilized, transparent, developmental material); **Polypropylene** (composition: normal ethylene random copolymer with a hindered amine light stabilizer, with nucleator; features: gamma radiation stabilized, transparent, developmental material)

Laboratory testing of this material has demonstrated that it retains color, elongation at break, and resistance to dart drop impact and penetration extremely well after irradiation and aging. In these respects it is very suitable for packaging medical devices.

Four principal techniques were used to achieve improvements in clarity and radiation tolerance of polypropylene: ethylene copolymerization, additives, processing improvements, and novel molecular characteristics. While any of these can be used to obtain some improvement in resin properties, the enhancement of properties such as clarity and radiation tolerance in polypropylene is usually best affected by a combination of these methods.

These techniques were used to design a polypropylene sheet that draws radiation tolerance and clarity from a combination of ethylene content, molecular structure, antioxidant additives, and forming technique. The material was produced from a novel type of copolymer of propylene and containing a hindered amine light stabilizer, but no nucleator. The sheet was blown with minimal orientation in an apparatus that provided exceptionally rapid chilling of the bubble. The result was a sheet containing a minimum of the hazy and radiation sensitive alpha crystalline form of polypropylene and a maximum of very clear, radiation tolerant disordered amorphous and slightly ordered smectic polypropylenes.

This material is far superior in terms of toughness and resistance to radiation as compared to two other test materials: 1) a sheet produced from a propylene homopolymer containing a similar radiation stabilization package and 2) a sheet prepared from a

normal ethylene random copolymer containing a similar radiation stabilization package and a powerful polypropylene nucleating agent.

The superior performance of the material is also demonstrated by its retention of elongation at break and resistance to dart impact and puncture. The material's radiation tolerance is directly attributable to a design that incorporates contributions from all four of the significant factors in improving polypropylene performance. The use of random ethylene comonomer, unique molecular characteristics related to the incorporation of the random ethylene, a special process involving extremely rapid chilling of the blown melt, and a proper selection of additives all contribute synergistically to the result. The four important design factors combined have produced a highly radiation tolerant, very clear polypropylene sheet for use in medical device packaging.

Reference: Portnoy, R. C., Gulla, C. T., Kozimor, R. A., *Extremely Clear, Radiation Tolerant Polypropylene Sheet For Medical Device Packaging*, supplier technical report — Exxon Chemical Company.

Rexene: 13R9A (composition: random ethylene copolymers; features: gamma radiation stabilized)

Samples were exposed to 3.0 and 5.0 Mrads. The yellowness index, both light and dark, changes very little. Specimens exposed to nominal doses of gamma radiation undergo an increase in melt flow rate. The increase from a nominal 7.0 MFR to about 40 is a result of the chain scission effect gamma radiation has on polypropylene. Despite the scission effect, specimens maintain tensile strength and ultimate elongation essentially identical to the non irradiated control samples up through a nominal 3.0 Mrad dosage. At the higher dosage of nominal 5.0 Mrads, the ultimate elongation declines without any significant increase in tensile strength. The approximate 600% ultimate elongation obtained with the highest dosage still indicates a ductile, flexible, nonbrittle specimen. The yellowness index increases with increasing radiation dosages (range is from -1.7 for the control to about 5.0 for the highest dosage). Plaques exposed to fluorescent light decreased in yellowness to approach a neutral blue yellow color, while those kept in sealed dark containers increased slightly in yellowness.

Accelerated testing was performed on pellets, tensile bars and plaques exposed to nominal 1.5, 3.0 and 5.0 Mrads. The specimens were then separated into two groups, each with the varying Co-

balt 60 dosages. One group was maintained at 40°C and the other at 60°C in hot air circulating ovens. Specimens at 40°C showed essentially no change over the test period regardless of dosage. Specimens at 60°C retained ductility and tensile strength over the test period. At all test levels, both ultimate elongation and tensile strength remain essentially constant.

Reference: *From Rexene Technology: Radiation Resistant Polypropylenes*, supplier technical report (EPP 7037 10/87 4M JP) — jRexene Products Company, 1987.

Rexene: 13R9A (composition: random ethylene copolymers; features: gamma radiation stabilized)

Rexene proprietary additive packages for polypropylene allow the modified resin to be exposed to sterilizing doses (5 Mrads) of gamma radiation and maintain useful physical properties for at least four years (at room temperature) after exposure.

Tensile bars of radiation resistant polypropylene (PP13R15A Lot 24669) were also tested after accelerated aging at both 80°C and 120°C for 3 and 6 weeks; bars were suspended in a forced draft oven. The samples were irradiated with a nominal 5.0 Mrads of gamma radiation from a Cobalt 60 source. After irradiation and ASTM conditioning, physical properties were determined. After 3 weeks at 80°C tensile strength at yield increases from 25.3 MPa immediately after irradiation to 28.6 MPa. Elongation at break decreases to 300% from 680%. Yellowness index increases from 5.0 to 6.9, an amount barely detectable to the human eye in side-by-side comparisons. After 6 weeks at 80°C, samples maintain their physical properties. A group of tensile bars from the same batch were also stored in a controlled environment of 23°C and 50% relative humidity. After one year, physical property values lay between the values obtained for 0 and 3 weeks at 80°C. These results support the contention that three weeks at 80°C is equivalent to a year at ambient conditions.

Accelerated aging at 120°C can induce embrittlement and failure. Tensile bars were molded from Lot 24669 and then exposed to doses of 3.1 and 3.0 Mrads on consecutive days. After one day at 120°C embrittlement is evident in the substantial reduction of elongation at break. Oven aging was stopped after 7 days when embrittlement was so severe the tensile bars broke before a yield point was encountered. Also the yellowness index increased to nearly 20. Results from other experiments indicate that the radiation resistant polypropylene

can withstand oven aging at 120°C for a week, with a significant increase in yellowness index. Other experiments show that a single dose of 6 Mrads does not cause failure. It appears as if two equal doses a day apart are more damaging than a single dose of double intensity.

The nature of the radiation source may influence post irradiation performance of polypropylene. To test this concern, samples of tensile bars made from PP13R9A Lot 24043 random copolymer were sent to four different locations and irradiated at a nominal 3.0 Mrads. Three locations used Cobalt 60 and one used Cesium 137 as primary sources of gamma radiation. Locations with Cobalt 60 had source intensities ranging from 1.6 megacuries to 3.5 megacuries. The Cesium source had an intensity of 1.5 megacuries. The yellowness index is slightly higher in samples exposed to the 2.0 megacurie source of Cobalt 60 compared to samples exposed to the 1.6 or 3.5 megacurie source of the same isotope. Compared to Cobalt 60 sources, radiation from Cesium 137 appears to cause significantly more yellow color in the radiation resistant polypropylene. Cobalt 60 emits two gammas at 1.17 Mev and 1.33 Mev and a beta with 0.31 Mev. Cesium 137 emits a 1.18 Mev gamma and a 0.51 Mev beta. Perhaps the more energetic beta causes more yellow color, or perhaps the decay of other isotopes causes the difference.

Reference: Lucas, Ben M., Paton, Samuel J., Thakker, M. T., *Radiation Resistant Polypropylene*, Medical Plastics '90 International Conference, Malmö, Sweden, conference proceedings — Rexene Products Company, 1990.

19.13.7 Ethylene Oxide (EtO) Resistance

Himont: Profax 6323 The tensile yield after 1 cycle of HCFC-124/EtO shows a decrease of 20%. After 2 cycles of the same carrier gas mixture there is no such decrease in tensile yield which suggests that a decrease in tensile strength is not typical. The tensile modulus is affected by EtO sterilization and is seen 8 weeks after EtO exposure. The tensile modulus after 2 cycles of EtO decreases by 78%. The instrumented impact data after sterilization appears to show a slight decrease.

Reference: Hermanson, Nancy J., *Effects Of Alternate Carriers Of Ethylene Oxide Sterilant On Thermoplastics*, supplier technical report (301-02018) — Dow Chemical Company.

Rexene: 13R9A (composition: random ethylene copolymers; features: gamma radiation stabilized)

Polypropylene can be ethylene oxide sterilized as the polymer is chemically very inert.

Reference: Lucas, Ben M., Paton, Samuel J., Thakker, M. T., *Radiation Resistant Polypropylene*, Medical Plastics '90 International Conference, Malmö, Sweden, conference proceedings — Rexene Products Company, 1990.

Quantum: Petrothene Waste containers and bags extruded from polypropylene can be sterilized by ethylene oxide.

Reference: *Performance Polyolefins For The Healthcare Market*, supplier marketing literature (6615/591) — Quantum Chemical Corporation, 1991.

19.13.8 Steam Resistance

Rexene: 13R9A (composition: random ethylene copolymers; features: gamma radiation stabilized)

Polypropylene items can be sterilized in autoclaves as polypropylene can withstand temperatures up to 125°C.

Reference: Lucas, Ben M., Paton, Samuel J., Thakker, M. T., *Radiation Resistant Polypropylene*, Medical Plastics '90 International Conference, Malmö, Sweden, conference proceedings — Rexene Products Company, 1990.

Quantum: Petrothene Waste containers and bags extruded from polypropylene can be autoclaved.

Reference: *Performance Polyolefins For The Healthcare Market*, supplier marketing literature (6615/591) — Quantum Chemical Corporation, 1991.

Table 19.14 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE
Material Supplier/Name	HIMONT PROFAX PF511
Material Note	gamma radiation stabilized, high flow
Reference No.	69

EXPOSURE CONDITIONS

Type	Gamma Radiation
Radiation Dose (Mrads)	5

PROPERTIES RETAINED (%)

Tensile Strength	100 (jb)
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SURFACE AND APPEARANCE

Δ Yellowness Index	2
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Table 19.15 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE						
Material Supplier/Name	REXENE 13R9A						
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	104	104	104	104	104	104	104

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Details	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60
Radiation Dose (Mrads)	6.1	6.1	6.1	5	5	5	5
Note	doses of 3.1 Mrads and 3.0 Mrads on consecutive days	doses of 3.1 Mrads and 3.0 Mrads on consecutive days	doses of 3.1 Mrads and 3.0 Mrads on consecutive days				

POST EXPOSURE CONDITIONING

Note	type: ASTM conditioning	type: ASTM conditioning	type: ASTM conditioning	type: ASTM conditioning	type: ASTM conditioning	type: ASTM conditioning	type: ASTM conditioning
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POST EXPOSURE CONDITIONING II

Note		type: forced draft air oven	type: forced draft air oven		type: forced draft air oven	type: forced draft air oven	type: ambient conditions
Temperature (°C)		120	120		80	80	23
Time (hours)	0	24	168	0	504	1008	8760

PROPERTIES RETAINED (%)

Tensile Strength @ Yield	106.7	113.1	0	94.1	106.3	106.3	104.8
Elongation	100	6.5	3.2	100	50	60	53.3

SURFACE AND APPEARANCE

Δ Yellowness Index	5.9	9.7	18.7	1	2.9	3.2	2.3
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Table 19.16 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	104	104	104	104	104	104

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Details	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cesium 137
Radiation Dose (Mrads)	5	5	3	3	3	3
Note			intensity: 1.6 megacuries	intensity: 2.0 megacuries	intensity: 3.5 megacuries	intensity: 1.5 megacuries

PRE EXPOSURE CONDITIONING

Preconditioning Note	type: reprocessing	type: reprocessing				
Times Reprocessed	0	7				

POST EXPOSURE CONDITIONING

Note	type: ASTM conditioning	type: ASTM conditioning				
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PROPERTIES RETAINED (%)

Tensile Strength @ Yield	103.4	97.8	98.9	99.3	96.7	95.9
Elongation	91.7	63.3	93.3	86.7	73.3	83.3

SURFACE AND APPEARANCE

Δ Yellowness Index	2.1	1.4	0.9	3	1.4	10
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Table 19.17 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	99	99	99	98	98	98

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	1.5	3	5

POST EXPOSURE CONDITIONING

Note	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light
Time (hours)	336	336	336	2190	2190	2190

PROPERTIES RETAINED (%)

Tensile Strength @ Yield	100.8	101.8	102.3	100.7	100.5	101
Elongation	100	100	82.9	100	100	82.9
Melt Flow Rate	430.6	736.1	625	578.6	857.1	652.9

SURFACE AND APPEARANCE

Δ Yellowness Index	3.4	4.9	6.7	2.4	2.9	3
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Table 19.18 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	98	98	98	98	98	98

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	1.5	3	5

POST EXPOSURE CONDITIONING

Note	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light
Time (hours)	4380	4380	4380	8766	8766	8766

PROPERTIES RETAINED (%)

Tensile Strength @ Yield	100.7	100.2	101	99.5	98.3	97.8
Elongation	100	100	75.7	100	100	100
Melt Flow Rate	567.6	689.2	689.2	691.7	805.6	534.7

SURFACE AND APPEARANCE

Δ Yellowness Index	2.4	2.4	2.8	2.2	2.2	2.3
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Table 19.19 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	98	98	98	99	99	99

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	15	3	5

POST EXPOSURE CONDITIONING

Note	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light	type: storage under fluorescent light
Time (hours)	13140	13140	13140	17531	17531	17531

PROPERTIES RETAINED (%)

Tensile Strength @ Yield	99.3	99.5	99	100	100.2	101
Elongation	100	100	100	100	100	100
Melt Flow Rate	691.7	805.6	534.7	554.1	770.3	752.7

SURFACE AND APPEARANCE

Δ Yellowness Index	1.8	2	2	0.9	0.7	0.7
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Table 19.20 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	99	99	99	98	98	98

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	1.5	3	5

POST EXPOSURE CONDITIONING

Note	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark
Time (hours)	336	336	336	2190	2190	2190

SURFACE AND APPEARANCE

Δ Yellowness Index	3.5	4.9	6.7	4.5	5.7	6.9
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Table 19.21 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	98	98	98	99	99	99

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	1.5	3	5

POST EXPOSURE CONDITIONING

Note	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark
Time (hours)	4380	4380	4380	8765	8765	8765

SURFACE AND APPEARANCE

Δ Yellowness Index	3.4	5.2	7.1	5.1	7.2	7.1
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Table 19.22 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	REXENE 13R9A					
Material Note	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized	random ethylene copolymer; gamma radiation stabilized
Reference No.	98	98	98	99	99	99

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	1.5	3	5	1.5	3	5

POST EXPOSURE CONDITIONING

Note	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark	type: storage in dark
Time (hours)	13140	13140	13140	17531	17531	17531

SURFACE AND APPEARANCE

Δ Yellowness Index	5.5	6.6	7.4	5.6	6.6	7.3
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Table 19.23 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE					
Material Supplier/Name	EXXON					
Material Note	polypropylene homopolymer with a hindered amine light stabilizer, no nucleator; gamma radiation stabilized, transparent, developmental material	novel polypropylene copolymer with a hindered amine light stabilizer, no nucleator; gamma radiation stabilized, transparent, developmental material	novel polypropylene copolymer with a hindered amine light stabilizer, no nucleator; gamma radiation stabilized, transparent, developmental material	normal ethylene random copolymer with a hindered amine light stabilizer, with nucleator; gamma radiation stabilized, transparent, developmental material		
Reference No.	67	67	67	67	67	67

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Details	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60
Radiation Dose (Mrads)	2.5	5	2.5	5	2.5	5
Note	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr

POST EXPOSURE CONDITIONING

Time (hours)	0	0	0	0	0	0
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PROPERTIES RETAINED (%)

Elongation	77.1	25.7	92	79	91	78
Dart Impact (total energy)	47.6	28.6				

Table 19.24 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE			
Material Supplier/Name	EXXON			
Material Note	novel polypropylene copolymer with a hindered amine light stabilizer, no nucleator; gamma radiation stabilized, transparent, developmental material	novel polypropylene copolymer with a hindered amine light stabilizer, no nucleator; gamma radiation stabilized, transparent, developmental material	normal ethylene random copolymer with a hindered amine light stabilizer, with nucleator; gamma radiation stabilized, transparent, developmental material	
Reference No.	67	67	67	67

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Details	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60	source: Cobalt 60
Radiation Dose (Mrads)	2.5	5	2.5	5
Note	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr	dose rate: 10 kGy/hr

POST EXPOSURE CONDITIONING

Note	type: aging	type: aging	type: aging	type: aging
Time (hours)	504	504	504	504

PROPERTIES RETAINED (%)

Elongation	95	79	68	0
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Table 19.25 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE				
Material Supplier/Name	EASTMAN TENITE				
Material Note	general purpose grade	general purpose grade	general purpose grade	general purpose grade	general purpose grade
Reference No.	55	55	55	55	55

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	2.5	2.5	2.5	2.5	2.5
Note	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.

POST EXPOSURE CONDITIONING

Note		type: accelerated aging	type: accelerated aging	type: accelerated aging	type: accelerated aging
Temperature (°C)		43.3	43.3	43.3	43.3
Time (hours)	0	720	1440	2880	4320

PROPERTIES RETAINED (%)

Elongation	16	16	16	16	16
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SURFACE AND APPEARANCE

Δb Color	6.3	7.1	6.9	6.8	7.1
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Table 19.26 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE				
Material Supplier/Name	EASTMAN TENITE P7673-960A				
Material Note	melt flow rate: 18 g/10 min.; gamma radiation stabilized				
Reference No.	55	55	55	55	55

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	2.5	2.5	2.5	2.5	2.5
Note	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.

POST EXPOSURE CONDITIONING

Note		type: accelerated aging	type: accelerated aging	type: accelerated aging	type: accelerated aging
Temperature (°C)		43.3	43.3	43.3	43.3
Time (hours)	0	720	1440	2880	4320

PROPERTIES RETAINED (%)

Elongation	71.4	66.7	83.3	73.8	73.8
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SURFACE AND APPEARANCE

Δb Color	6.1	5.4	5.4	6	6
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Table 19.27 Effect of Gamma Radiation Sterilization on Polypropylene

Material Family	POLYPROPYLENE				
Material Supplier/Name	EASTMAN TENITE P7673-984A				
Material Note	melt flow rate: 18 g/10 min.; gamma radiation stabilized	melt flow rate: 18 g/10 min.; gamma radiation stabilized	melt flow rate: 18 g/10 min.; gamma radiation stabilized	melt flow rate: 18 g/10 min.; gamma radiation stabilized	melt flow rate: 18 g/10 min.; gamma radiation stabilized
Reference No.	55	55	55	55	55

EXPOSURE CONDITIONS

Type	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation	Gamma Radiation
Radiation Dose (Mrads)	2.5	2.5	2.5	2.5	2.5
Note	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.	dose rate: 0.1 Mrads/hr.

POST EXPOSURE CONDITIONING

Note		type: accelerated aging	type: accelerated aging	type: accelerated aging	type: accelerated aging
Temperature (°C)		43.3	43.3	43.3	43.3
Time (hours)	0	720	1440	2880	4320

PROPERTIES RETAINED (%)

Elongation	57.5	68.5	65.8	49.3	57.5
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SURFACE AND APPEARANCE

Δb Color	1.25	0.95	1.35	1.25	1.15
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Table 19.28 Effect of Ethylene Oxide Sterilization on Polypropylene

Material Family	POLYPROPYLENE							
Material Supplier/Name	HIMONT PROFAX 6323							
Reference No.	6	6	6	6	6	6	6	6

EXPOSURE CONDITIONS

Type	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide
Details	12% EtO and 88% Freon	12% EtO and 88% Freon	12% EtO and 88% Freon	12% EtO and 88% Freon	8.6% EtO and 91.4% HCFC-124	8.6% EtO and 91.4% HCFC-124	8.6% EtO and 91.4% HCFC-124	8.6% EtO and 91.4% HCFC-124
Concentration	600 mg/l	600 mg/l	600 mg/l	600 mg/l				
Number of Cycles	1	1	2	2	1	1	2	2
Note	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.
Temperature (°C)	48.9	48.9	48.9	48.9	48.9	48.9	48.9	48.9
Time (hours)	6	6	6	6	6	6	6	6

PRE EXPOSURE CONDITIONING

Preconditioning Note	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%
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POST EXPOSURE CONDITIONING

Note	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg	type: aeration; pressure: 127 mm Hg
Temperature (°C)	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2

POST EXPOSURE CONDITIONING II

Note	type: ambient conditions	type: ambient conditions	type: ambient conditions	type: ambient conditions	type: ambient conditions	type: ambient conditions	type: ambient conditions	type: ambient conditions
Time (hours)	168	1344	168	1344	168	1344	168	1344

PROPERTIES RETAINED (%)

Tensile Strength @ Yield	99.4	100	98.6	96.1	94	80	97.9	98.8
Elongation	156.7	143.6	131	83.6	94	159.4	84.2	121.8
Modulus	69.6	109.8	54.3	20.7	23.4	96.2	83.2	22.3
Dart Impact (total energy)	128.6	100	164.3	42.9	114.3	142.9	178.6	142.9
Dart Impact (peak energy)	71.4	71.4	100	35.7	78.6	107.1	92.9	100

SURFACE AND APPEARANCE

ΔE Color	0.24	0.05	0.05	0.13	0	0.1	0.11	0.18
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Table 19.29 Effect of Ethylene Oxide Sterilization on Polypropylene

Material Family	POLYPROPYLENE			
Material Supplier/Name	HIMONT PROFAX 6323			
Reference No.	6	6	6	6

EXPOSURE CONDITIONS

Type	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide	Ethylene Oxide
Details	12% EtO and 88% Freon	12% EtO and 88% Freon	8.6% EtO and 91.4% HCFC-124	8.6% EtO and 91.4% HCFC-124
Concentration	600 mg/l	600 mg/l		
Number of Cycles	1	1	1	1
Note	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.	RH: 60%; test lab: Ethox Corp.
Temperature (°C)	48.9	48.9	48.9	48.9
Time (hours)	6	6	6	6

PRE EXPOSURE CONDITIONING

Preconditioning Note	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%	time: 18 hours; temperature: 37.8°C; RH: 60%
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POST EXPOSURE CONDITIONING

Note	type: aeration; note: 10 air changes per hour	type: aeration; note: 30 air changes per hour	type: aeration; note: 10 air changes per hour	type: aeration; note: 30 air changes per hour
Temperature (°C)	32.2	54.4	32.2	54.4

RESIDUALS (PPM)

Residuals Determined	ethylene oxide	ethylene oxide	ethylene oxide	ethylene oxide
Little or No Aeration	451	451	415	415
17 hour Aeration		34		40
24 hour Aeration	138	25	163	36
48 hour Aeration	49	14	140	26
72 hour Aeration	25		64	

19.14 Chemical and Environmental Stress Crack Resistance

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Acetaldehyde			23			8						no significant effect	Phillips Marlex
Acetic Acid		5	23	28		5						no visible change	Eastman Ektar FB PG001; 10% gl.fib.
		5	23	365		8	0.1	0.1			275	slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	20	180		9	<0.5		<3				Network Pol. Polyfine
		10	21			8						satisfactory resistance	Solvay Fortilene
		10	60			8						"	"
		10	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	60	180		9	<.5		<3				Network Pol. Polyfine
		40	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		40	20	180		9	<0.5		<3				Network Pol. Polyfine
		50	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		50	21			8						satisfactory resistance	Solvay Fortilene
		50	60			8						"	"
		50	80	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	glacial	50	100			5						some attack	Solvay Fortilene
		97	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		97	20	180		9	<0.5		<3				Network Pol. Polyfine
	glacial	97	80	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			23	7	0.25%	8					90		LNP ; 30% gl.fib.
			23	7		9					95		"
			60			8						satisfactory resistance	Solvay Fortilene
Acetic Anhydride			21			8						"	"
			60			8						"	"
Acetone			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9	<0.5		<3				Network Pol. Polyfine
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			23	28		4				73	475	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			23	365		7	2.2	1				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9	<.5		<3				Network Pol. Polyfine
Acetonitrile			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Acetophenone			20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		4	0.5-5						Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		4	0.5-5						Network Pol. Polyfine
			100			2						unsatisfactory resistance	Solvay Fortilene
Acetylene			23			5						may cause soft./ swell.	Phillips Marlex
Acriflavine		2	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		2	80	30		9						"	"
Acrylics	emulsions		20	30		9						"	"
	"		60	30		9						"	"
Aircraft Fuels	115/145 ocatane		20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
	turbine		20	30		7						"	"
			21			5						some attack	Solvay Fortilene
	aviation		23	365		2	12.2	4.5				swelled and bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			5						some attack	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
	turbine		60	30		4						"	"
Aircraft Turbine Fuels	aviation		20	30		7						suitable for most applic.	"
	"		60	30		4						ext. absorp./perm.; short use maybe OK	"
Almond Oil			23			8						no significant effect	Phillips Marlex
Alum	all types		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		21			8						satisfactory resistance	Solvay Fortilene
	"		60			8						"	"
	"		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Aluminum Ammonium Sulfate			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
Aluminum Chloride			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60	30		8						satisfactory resistance	Solvay Fortilene
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene
Aluminum Fluoride			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60	30		8						satisfactory resistance	Solvay Fortilene
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Aluminum Hydroxide			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Aluminum Nitrate			21			8						"	"
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			8						"	"
Aluminum Potassium Sulfate			21			8						"	"
			60			8						"	"
Aluminum Sulfate			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ammonia	aqueous solution	10	20	180		9	<0.5		<3			negligible effect	Network Pol. Polyfine
		30	20			9							Himont Pro-Fax; 76x0.64 mm specimens
		30	20	180		9							Network Pol. Polyfine
	aqueous solution	30	21	30		8	<0.5		<3			satisfactory resistance	Solvay Fortilene
		"	60			8						"	"
	dry gas	20	20			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		21	20			8						satisfactory resistance	Solvay Fortilene
	anhydrous	23	20			8						no significant effect	Phillips Marlex
	anhydrous	60	20	30		8						satisfactory resistance	Solvay Fortilene
		60	60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	dry gas	60	20			8						satisfactory resistance	Solvay Fortilene
		60	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ammonium Bifluoride			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Ammonium Carbonate	saturated solution	20	30			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		21				8						satisfactory resistance	Solvay Fortilene
		23				8						no significant effect	Phillips Marlex
	saturated solution	60	30			8						satisfactory resistance	Solvay Fortilene
		60				9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		100				8						satisfactory resistance	Solvay Fortilene
Ammonium Chloride	saturated solution	20	30			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		21				8						satisfactory resistance	Solvay Fortilene
		23				8						no significant effect	Phillips Marlex
	saturated solution	60	30			8						satisfactory resistance	Solvay Fortilene
		60				9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		100				5						some attack	Solvay Fortilene
Ammonium Fluoride		20	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	60			9						"	"
		25	21	30		8						satisfactory resistance	Solvay Fortilene
		25	60			8						"	"
		23	23			8						no significant effect	Phillips Marlex
Ammonium Hydroxide		10	20	30		9	0	-0.1				negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	23			8						slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
		10	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	81	3		8						LNP ; 30% gl.fib.	
		21	21	7	0.25%	8						satisfactory resistance	Solvay Fortilene
		23	23			8						no significant effect	Phillips Marlex
		23	7			8						LNP ; 30% gl.fib.	
		23	7			9						"	"
		60	60			8						satisfactory resistance	Solvay Fortilene
Ammonium Meta-phosphate	saturated	20	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		60	60			9						"	"

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Ammonium Nitrate	saturated solution		20	30		9						"	
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Ammonium Persulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		60	30		9						"	"
Ammonium Phosphate			23			8						no significant effect	Phillips Marlex
Ammonium Sulfate	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Ammonium Sulfide	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
Ammonium Sulfide			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ammonium Thiocya- nate	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Amyl Acetate			20	30		7						suitable for most applic.	"
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Amyl Alcohol			20	30		9						negligible effect	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			100			2						unsatisfactory resistance	Solvay Fortilene
Amyl Chloride			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Aniline			20	30		9						negligible effect	"
			20	180		9	<0.5		<3				Network Pol. Polyfine
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9	<.5		<3				Network Pol. Polyfine
			100			5						some attack	Solvay Fortilene
Anisole			20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		4	0.5-5						Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		4	0.5-5						Network Pol. Polyfine
			100			2						unsatisfactory resistance	Solvay Fortilene
Antifreeze			23			8						no significant effect	Phillips Marlex
	ethylene glycol; Prestone		23	28		9				98	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
Antimony Chloride			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Antimony Trichloride			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Aqua Regia			20	30		5						limited absorp./attack; poss. stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
			21			5						some attack	Solvay Fortilene
			23			4						oxidizing agent	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		5						limited absorp./attack; poss. stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
Arsenic Acid			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Barium Carbonate	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Barium Chloride	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene
Barium Hydroxide			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Barium Soap Grease			21			8						satisfactory resistance	Solvay Fortilene
			60			5						some attack	"
Barium Sulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Barium Sulfide	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Beer			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Benzaldehyde			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Benzene			20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		4	0.5-5					may cause soft./swell.	Network Pol. Polyfine
			23			5						ext. absorp./perm.; short use maybe OK	Phillips Marlex
			60	30		4							Himont Pro-Fax; 76x0.64 mm specimens
			60	180		5	>5		>8				Network Pol. Polyfine
Benzene			81	3		2				59		ext. absorp./perm.; short use maybe OK	LNP ; 30% gl.fib.
			100	30		4							Himont Pro-Fax; 76x0.64 mm specimens
			100	180		5	>5		>8				Network Pol. Polyfine
Benzoic Acid			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Benzoyl Chloride			23			8						no significant effect	Phillips Marlex
Benzyl Alcohol			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			23	28		9				99	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			60			8						satisfactory resistance	Solvay Fortilene
			80	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Benzyl Chloride			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note	
							Weight	Thick-ness	Volume	Tensile Strength	Elongation			
Bismuth Carbonate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
			21			8						satisfactory resistance	Solvay Fortilene	
			60			8						"	"	
	saturated	60	30	9	negligible effect	Himont Pro-Fax; 76x0.64 mm specimens								
Bleach	Chlorox	5	23	28		9				96	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.	
Borax			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
			21			8						satisfactory resistance	Solvay Fortilene	
			60			8						"	"	
			60	30	9	negligible effect						Himont Pro-Fax; 76x0.64 mm specimens		
			100	8	satisfactory resistance	Solvay Fortilene								
Boric Acid			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
			21			8						satisfactory resistance	Solvay Fortilene	
			23			8						no significant effect	Phillips Marlex	
			60	8	satisfactory resistance	Solvay Fortilene								
			60	30	9	negligible effect						Himont Pro-Fax; 76x0.64 mm specimens		
Brake Fluids			21		0.25%	8						satisfactory resistance	Solvay Fortilene	
			23			7						9	102	LNP ; 30% gl.fib.
			23			7						9	97	"
			60			5						some attack	Solvay Fortilene	
			81			3						7	87	LNP ; 30% gl.fib.
Brines	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
	solution	21	8			satisfactory resistance						Solvay Fortilene		
		23	8			no significant effect						Phillips Marlex		
		60	8	satisfactory resistance	Solvay Fortilene									
	saturated	60	30	9	negligible effect	Himont Pro-Fax; 76x0.64 mm specimens								
		100	8	satisfactory resistance	Solvay Fortilene									
Bromic Acid			21			2						unsatisfactory resistance	"	
			23			4						oxidizing agent	Phillips Marlex	
			60			2						unsatisfactory resistance	Solvay Fortilene	
Bromine	bromine liquid		20	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens	
	bromine water	20	4			ext. absorp./perm.; poss. stress crack agent						"		
	21	2	unsatisfactory resistance			Solvay Fortilene								
Bromine	bromine water		21			2						unsatisfactory resistance	Solvay Fortilene	
	bromine liquid	23	4			oxidizing agent						Phillips Marlex		
		60	2			unsatisfactory resistance						Solvay Fortilene		
	bromine water	60	2			"						"		
Butane			23			5						may cause soft./ swell.	Phillips Marlex	
Butyl Acetate			20	180		5	>5		>8				unsatisfactory resistance	Network Pol. Polyfine
			21			2							may cause soft./ swell.	Solvay Fortilene
			23			5							Phillips Marlex	"
			23	365		4	6.3	1.8			slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs		
			60			2			unsatisfactory resistance	Solvay Fortilene				
			60	30	4	ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens							
			60	180	5	>5		>8			Network Pol. Polyfine	"		
			100	30	4	ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens							
			100	180	5	>5		>8			Network Pol. Polyfine	"		
			Butyl Acrylate			21			2					
23	5	may cause soft./ swell.				Phillips Marlex								
60	2	unsatisfactory resistance				Solvay Fortilene								
Butyl Alcohol	butanol		21	30		8						satisfactory resistance	"	
	"	23	8			no significant effect						Phillips Marlex		
	"	60	8			satisfactory resistance						Solvay Fortilene		
	"	100	9			negligible effect						Himont Pro-Fax; 76x0.64 mm specimens		
Butyl Phthalate			23			5						may cause soft./ swell.	Phillips Marlex	
Butyrolactone (α-)			23	28		9				100	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.	
Calcium Bisulfate			21			8						satisfactory resistance	Solvay Fortilene	
			60			8						"	"	
Calcium Bisulfide			23			8						no significant effect	Phillips Marlex	
Calcium Bisulfite			23			8						"	"	
Calcium Carbonate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
			21			8						satisfactory resistance	Solvay Fortilene	
			23			8						no significant effect	Phillips Marlex	
	saturated	60	8	satisfactory resistance	Solvay Fortilene									
		60	30	9	negligible effect	Himont Pro-Fax; 76x0.64 mm specimens								
		100	8	satisfactory resistance	Solvay Fortilene									

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Calcium Chlorate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Calcium Chloride		2.5	23	365		8	0.1	-0.4				slightly yellowed	Eastman Tenite 4231; 50.8x3.2 mm discs
		50	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		50	60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			5						some attack	"
Calcium Hydroxide			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Calcium Hydroxide			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Calcium Hypochlorite		20	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	60	30		7						suitable for most applic.	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Calcium Nitrate			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Calcium Phosphate		50	20	30		9						"	"
Calcium Soap Grease			21			8						satisfactory resistance	Solvay Fortilene
			60			5						some attack	"
Calcium Sulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Calcium Sulfite			20	30		9						"	"
			60	30		9						"	"
Camphor	oil		23			5						may cause soft./ swell.	Phillips Marlex
Carbon Dioxide	dry		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	wet		20	30		9						"	"
	dry		21			8						satisfactory resistance	Solvay Fortilene
	wet		21			8						"	"
			23			8						no significant effect	Phillips Marlex
	dry		60			8						satisfactory resistance	Solvay Fortilene
	wet		60			8						"	"
	dry		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	wet		60	30		9						"	"
Carbon Disulfide		40	20	180		4	0.5-5					suitable for most applic.	Network Pol. Polyfine
			20	30		7						some attack	Himont Pro-Fax; 76x0.64 mm specimens
			21			5						may cause soft./ swell.	Solvay Fortilene
			23			5						swelled and slightly bleached	Phillips Marlex
			23	365		3	18.3	3.9				unsatisfactory resistance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						ext. absorp./perm.; short use maybe OK	Solvay Fortilene
			60	30		4						"	Himont Pro-Fax; 76x0.64 mm specimens
Carbon Monoxide			20	30		9						negligible effect	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Carbon Tetrachloride			20	30		4						ext. absorp./perm.; short use maybe OK	"
			20	180		5	>5		>8			"	Network Pol. Polyfine
			21			2						unsatisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Carbon Tetrachloride			23			5						may cause soft./ swell.	Phillips Marlex
			23	30		1	29			57			"
			23	365		2	43	7.3				swelled and slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		5	>5		>8				Network Pol. Polyfine
			81	3		1				45			LNP ; 30% gl.fib.
			100	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Carbonic Acid			100	180		5	>5		>8				Network Pol. Polyfine
			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
Castor Oil			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20			8						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Caustic Potash			60			8						satisfactory resistance	Solvay Fortilene
			10	20	180	9	<0.5		<3				Network Pol. Polyfine
			10	60	180	9	<.5		<3				"
			50	20	180	9	<0.5		<3				"
Caustic Soda			50	60	180	9	<.5		<3				"
			10	20	180	9	<0.5		<3				"
			10	60	180	9	<.5		<3				"
			10	100	180	9	<.5		<3				"
Cetyl Alcohol			50	20	180	9	<0.5		<3				"
			50	60	180	9	<.5		<3				"
			2-ethoxyethanol	21		8						satisfactory resistance	Solvay Fortilene
			"	23		8						no significant effect	Phillips Marlex
Chlorine	gas		60			8						satisfactory resistance	Solvay Fortilene
			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Chlorine	dry		21			8						satisfactory resistance	Solvay Fortilene
			20	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			21			5						some attack	"
			23			4						oxidizing agent	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60			2						"	"
			60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			70	30		1						"	"
			moist gas										
Chloroacetic Acid			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Chlorobenzene			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Chloroform			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		5	>5		>8				Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			23	365		2	26.7	4.8				severe swell., sl. bleach	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		1						no chemical resistance	Network Pol. Polyfine
			100	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			100	180		1						no chemical resistance	Network Pol. Polyfine
Chlorosulfonic Acid			10	20	180	1						"	"
			10	60	180	1						"	"
			10	100	180	1						"	"
			20	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23			4						oxidizing agent	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			100	30		1						"	"
Chocolate Syrup			23			8						no significant effect	Phillips Marlex

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Chrome Alum			20 60	30 30		9 9						negligible effect "	Himont Pro-Fax; 76x0.64 mm specimens "
Chromic Acid		1 1 10 10 10 50 50 50 50 80 80 80	20 20 60 21 60 20 21 60 60 20 21	180 180 30 30 30 30		9 9 7 8 8 7 8 8 7 7 8	<0.5 "		<3 "			negligible effect "	Network Pol. Polyfine "
	chromic/sulfuric acid		20 23	30 30		1 7						dissolves/disint. no signif. effect	Himont Pro-Fax; 76x0.64 mm specimens Phillips Marlex
	chromic/sulfuric acid		60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
Cider			20 21 60 60	30 30		9 8 8 9						negligible effect satisfactory resistance "	" Solvay Fortilene "
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Citric Acid		10 10 10 10	20 20 23 60	30 180 365 30		9 9 9 8 8 8	<0.5 0		<3 0.3			" no change in appearance negligible effect satisfactory resistance no significant effect satisfactory resistance	" Network Pol. Polyfine Eastman Tenite 4231; 50.8x3.2 mm discs Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene Phillips Marlex Solvay Fortilene
Clorox	Chlorox " " " " "		21 23 23 23 60 81 100	 7 7 3	0.25%	8 8 8 8 5 8				90 90 78		satisfactory resistance no significant effect "	Solvay Fortilene Phillips Marlex LNP ; 30% gl.fib. "
			81	3		5				78		satisfactory resistance	Solvay Fortilene LNP ; 30% gl.fib.
			100			8						satisfactory resistance	Solvay Fortilene
Cloves	clove oil		23			5						may cause soft./ swell. no significant effect	Phillips Marlex "
Coconut Oil			23			8							"
Cod Liver Oil			23			8							"
Copper Chloride	saturated		20 21 23 60	30 30		9 8 8 8						negligible effect satisfactory resistance no significant effect satisfactory resistance	Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene Phillips Marlex Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Copper Cyanide	"		20 23	30 30		9 8						" no significant effect	" Phillips Marlex
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Copper Fluoride	"		20 21 23 60	30 30		9 8 8 8						" satisfactory resistance no significant effect satisfactory resistance	" Solvay Fortilene Phillips Marlex Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Copper Nitrate	"		20 21 23 60	30 30		9 8 8 8						" satisfactory resistance no significant effect satisfactory resistance	" Solvay Fortilene Phillips Marlex Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Copper Sulfate		10	23 20 21 23 60	365 30 30		9 9 8 8 8	0	0.2				no change in appearance negligible effect satisfactory resistance no significant effect satisfactory resistance	Eastman Tenite 4231; 50.8x3.2 mm discs Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene Phillips Marlex Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Copppe Cyanide			21 60			8 8						satisfactory resistance "	Solvay Fortilene "

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Corn Oil			21 23 23 23 60			8 8 9 9 8						" no significant effect satisfactory resistance	" Phillips Marlex LNP ; 30% gl.fib. " Solvay Fortilene
Cottonseed Oil			20 20 21 23 60 60 60	30 180		9 9 8 8 8 9 9	<0.5		<3			negligible effect satisfactory resistance no significant effect satisfactory resistance negligible effect	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene Phillips Marlex Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Cresol			21 23 60			8 7 8						satisfactory resistance no signif. effect satisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Cuprous Chloride	saturated		20 21 60	30		9 8 8						negligible effect satisfactory resistance "	Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene "
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Cyclohexane			21 23 60			8 5 5						satisfactory resistance may cause soft./ swell. some attack	Solvay Fortilene Phillips Marlex Solvay Fortilene
Cyclohexanone			20 20 21 23 23 60 60 60	30 180 28		7 9 5 7 5 2 4 5	<0.5		<3			suitable for most applic. some attack no signif. effect no visible change unsatisfactory resistance ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene Phillips Marlex Eastman Ektar FB PG001; 10% gl.fib. Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Cyclohexyl Alcohol			20 20 21 23 60 60 60	30 180 30 180		9 9 8 8 5 7 4	<0.5		<3			negligible effect satisfactory resistance no significant effect some attack suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene Phillips Marlex Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Decalin			20 20 21 23 60 60 60 100 100	30 180 30 180		4 5 2 5 2 4 5 4 5	>5		>8			ext. absorp./perm.; short use maybe OK unsatisfactory resistance may cause soft./ swell. unsatisfactory resistance ext. absorp./perm.; short use maybe OK ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene Phillips Marlex Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Detergents		2 2 2	20 60 100	30 30 30		9 9 9						negligible effect " "	Himont Pro-Fax; 76x0.64 mm specimens " "
Dextrin			21 60			8 8						satisfactory resistance "	Solvay Fortilene "
Diacetone Alcohol			23			7						no signif. effect	Phillips Marlex
Dibutyl Phthalate			20 20 21 60 60 60 100	30 180		9 9 8 8 7 4 2	<0.5		<3			negligible effect satisfactory resistance " suitable for most applic. unsatisfactory resistance	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene " Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene
Dibutyl Phthalate			100 100	30 180		1 1						dissolves/disint. no chemical resistance	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Dichloroethane (1,2-)			23	28		4				67	675	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
Dichloroethylene			20 20 21	30 180		9 9 8	<0.5		<3			negligible effect satisfactory resistance	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note				
							Weight	Thick-ness	Volume	Tensile Strength	Elon-gation						
Diethanolamine			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens				
			21			8						satisfactory resistance	Solvay Fortilene				
			60			8						"	"				
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens				
Diethyl Ether			21			5						some attack	Solvay Fortilene				
			23			7						no signif. effect	Phillips Marlex				
			60			5						some attack	Solvay Fortilene				
Diethylamine			23			8						no significant effect	Phillips Marlex				
Diglycolic Acid			21			8						satisfactory resistance	Solvay Fortilene				
			23			8						no significant effect	Phillips Marlex				
			60			8						satisfactory resistance	Solvay Fortilene				
Diisooctyl Phthalate			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens				
			21			8						satisfactory resistance	Solvay Fortilene				
			60			8						"	"				
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens				
Dimethyl Phthalate			21			8						satisfactory resistance	Solvay Fortilene				
			60			8						"	"				
Dimethylformamide			23			8						no significant effect	Phillips Marlex				
Dioctyl Phthalate			23			7						no signif. effect	"				
Dioxane			20	180		4	0.5-5							Network Pol. Polyfine			
			60	180		4	0.5-5							"			
Dioxane (p-)			21			8						satisfactory resistance	Solvay Fortilene				
			23			7						no signif. effect	Phillips Marlex				
			60			5						some attack	Solvay Fortilene				
Dishwashing Deter-gents	Calgonite	1	21			8						satisfactory resistance	"				
	"	1	60			8						"	"				
	Cascade	10	81	3		8	91						LNP ; 30% gl.fib.				
Emulsifiers			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens				
			60	30		9						"	"				
Epichlorohydrin			23			5						may cause soft./ swell.	Phillips Marlex				
Ethyl Acetate			20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens				
			20	180		4	0.5-5							Network Pol. Polyfine			
			21			8						satisfactory resistance	Solvay Fortilene				
			23	28		4				69	575		Eastman Ektar FB PG001; 10% gl.fib.				
			23	30		4	5			80			Phillips Marlex				
			23	365		4	5	1.6					Eastman Tenite 4231; 50.8x3.2 mm discs				
			60			8						satisfactory resistance	Solvay Fortilene				
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens				
			60	180		4	0.5-5							Network Pol. Polyfine			
Ethyl Alcohol			in water	50	23	28	9						92	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.	
				50	23	365	9	0.2	0.1						no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs	
				95	23	365	9	0.2	0.5						"	"	
				96	20	30	9								negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
Ethyl Alcohol				96	20	180	9	<0.5		<3						negligible effect	Network Pol. Polyfine
				96	60	30	9								negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
				96	60	180	9	<.5		<3						negligible effect	Network Pol. Polyfine
				96	80	30	9								negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
				96	100	180	9	<.5		<3						negligible effect	Network Pol. Polyfine
					20	30	9								negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
					21		8								satisfactory resistance	Solvay Fortilene	
					21		8								"	"	
					23		8										
					23	28	9						93	100	no significant effect	Phillips Marlex	
					23	30	9	0						94		no visible change	Eastman Ektar FB PG001; 10% gl.fib.
					60		8								satisfactory resistance	Phillips Marlex	
					60		8								"	Solvay Fortilene	
					60	30	9								negligible effect	"	
					100		8								satisfactory resistance	Himont Pro-Fax; 76x0.64 mm specimens	
Ethyl Chloride				20	30		4								ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens	
				21			5								some attack	Solvay Fortilene	
				60			5								"	"	
				60	30		4								ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens	
Ethyl Ether				20	30		7								suitable for most applic.	"	
				20	180		4	0.5-5									Network Pol. Polyfine
				21			5								some attack	Solvay Fortilene	
				60			5								"	"	

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Ethylamine			21			8						satisfactory resistance	"
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Ethylene Chloride			21			2						unsatisfactory resistance	"
			23			5						may cause soft./ swell.	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
Ethylene Chlorohydrin			21			8						satisfactory resistance	"
			60			8						"	"
Ethylene Dichloride			20	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23	365		3	9.2	2				swelled and slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
Ethylene Glycol			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			23	7	0.25%	9							LNP ; 30% gl.fib.
			23	7		9							"
			23	365		9	0.1	0.3				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			81	3		8						93	LNP ; 30% gl.fib.
Ethylene Glycol Ethyl Ether			23	365		8	0.4	0.2				slightly yellowed	Eastman Tenite 4231; 50.8x3.2 mm discs
Ethylene Oxide			10	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
Fatty Acids	C6		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		60	30		9						"	"
Ferric Chloride		10	23	365		9	0.1	-0.1				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ferric Nitrate	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ferric Sulfate	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ferrous Chloride	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Ferrous Nitrate			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			100			5						some attack	"
Ferrous Sulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Fluorine			21			2						unsatisfactory resistance	Solvay Fortilene
			23			4						oxidizing agent	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
Fluosilicic Acid			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Flux	Kester # 1544		23	7	0.25%	9						96	LNP ; 30% gl.fib.
	"		23	7		6						82	"

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Formaldehyde	solution	35	23			8						no significant effect	Phillips Marlex
		35	23	365		8	0.2	-0.1				slightly yellowed	Eastman Tenite 4231; 50.8x3.2 mm discs
	solution	40	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		40	23			8						no significant effect	Phillips Marlex
		40	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9	<0.5		<3			Network Pol. Polyfine	
			21			8						Solvay Fortilene	
			60			8						"	
			100			5						some attack	"
Formic Acid		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	20	180		9	<0.5		<3			Network Pol. Polyfine	
		10	21			8						Solvay Fortilene	
		10	60			8						"	
		10	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	60	180		9	<.5		<3			Network Pol. Polyfine	
		85	23			8						Phillips Marlex	
			20	30		9						Himont Pro-Fax; 76x0.64 mm specimens	
			20	180		9	<0.5		<3			Network Pol. Polyfine	
			21			8						Solvay Fortilene	
Freon			23			8						no significant effect	Phillips Marlex
Fructose			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Fruit Juices			20	30		9						"	
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Fuel Oils			21			8						satisfactory resistance	Solvay Fortilene
			60			5						some attack	"
Furfural			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Gasoline	gas liquor		20	30		7						suitable for most applic.	"
			20	30		4						ext. absorp./perm.; short use maybe OK	"
			20	180		5	>5		>8				Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
	regular		23	7	0.25%	7				86			LNP ; 30% gl.fib.
			23	7		6				83			"
			23	28		4				56	775	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			23	365		2	13.7	4.5				swell., sl. bleach.	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		5	>5		>8				Network Pol. Polyfine
			81	3		2				59			LNP ; 30% gl.fib.
			100	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			100	180		5	>5		>8				Network Pol. Polyfine
Gear Oils	gearbox oil		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		60	30		7						suitable for most applic.	"
Gelatins			20	30		9						negligible effect	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Gelatins			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Glucose		20	20	30		9						"	"
		20	60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Glycerin			20	30		9	<0.5	0.2	<3			negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9						Network Pol. Polyfine	
			21			8						Solvay Fortilene	
			23			8						Phillips Marlex	
			23	365		9						no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						Solvay Fortilene	
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9						Network Pol. Polyfine	
			100			8						Solvay Fortilene	
			100	30		9						Himont Pro-Fax; 76x0.64 mm specimens	
Glycolic Acid			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						Solvay Fortilene	
Glycols			20	30		9	<0.5	0.2	<3			negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9						Network Pol. Polyfine	
			21			8						Solvay Fortilene	
			60			8						"	
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9						Network Pol. Polyfine	
			100			5						Solvay Fortilene	
Green Soap	solution		23	365		9	0.1	0.2				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
Heptane			21			2	11.1	4.4				unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			23	7		1						LNP ; 30% gl.fib.	
			23	7		1						"	
			23	28		4						no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			23	365		2						swelled and bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
Hexadecyl Alcohol			21			8						satisfactory resistance	"
			23			8						no significant effect	Phillips Marlex
			60			8						Solvay Fortilene	
Hexane			20	30		9	7			70		negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						Solvay Fortilene	
			23	30		2						Phillips Marlex	
			60			8						Solvay Fortilene	
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
Hydraulic Fluids	plus 12% Iodide	0.48	23	28		9				96	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
Hydriodic Acid			23			4						oxidizing agent	Phillips Marlex
Hydrobromic Acid		50	20	30		7						negligible effect; possible stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
			50	21		8						Solvay Fortilene	
			50	23		8						Phillips Marlex	
Hydrobromic Acid		50	60			8						satisfactory resistance	Solvay Fortilene
			50	60		7						negligible effect; possible stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
Hydrochloric Acid			2	20		9	<0.5	0.3	<3			negligible effect	"
			2	20		9						Network Pol. Polyfine	
			2	60		9						Himont Pro-Fax; 76x0.64 mm specimens	
			2	60		9						Network Pol. Polyfine	
			2	100		9						Himont Pro-Fax; 76x0.64 mm specimens	
			2	100		9						Network Pol. Polyfine	
			10	20		9						Himont Pro-Fax; 76x0.64 mm specimens	
			10	20		9						Network Pol. Polyfine	
			10	23		8						Phillips Marlex	
			10	23		7						LNP ; 30% gl.fib.	
			10	23		9						"	
			10	23		9						no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			10	60		9						Network Pol. Polyfine	
			10	80		9						Himont Pro-Fax; 76x0.64 mm specimens	
			10	81		6						LNP ; 30% gl.fib.	
			10	100		7						Himont Pro-Fax; 76x0.64 mm specimens	
			10	100		9						Network Pol. Polyfine	

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Hydrochloric Acid	with nitric acid "	20	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	21			8						satisfactory resistance	Solvay Fortilene
		20	60			8						"	"
		20	80	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	100			5						some attack	Solvay Fortilene
		30	20	30		7						negligible effect; possible stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
		30	20	180		9	<0.5		<3				Network Pol. Polyfine
		30	60	30		5						limited absorp./attack; poss. stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
		30	60	180		9	<.5		<3				Network Pol. Polyfine
		30	100	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
		30	100	180		1						no chemical resistance	Network Pol. Polyfine
		35	23			8						no significant effect	Phillips Marlex
		37	23	30		9	0			97			"
		50	20	30		5						limited absorp./attack; poss. stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
		50	80	30		1						dissolves/disint.	"
Hydrocyanic Acid			23			8						satisfactory resistance	Solvay Fortilene
						8						"	"
						9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
						8						no significant effect	Phillips Marlex
						7						negligible effect; possible stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
Hydrofluoric Acid		35	21			8						"	"
		35	60			8							
		40	20	30		9							
		50	23			8							
		60	20	30		7							
Hydrogen Chloride	dry gas "		20	30		9						negligible effect	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Hydrogen Peroxide		3	20	30		9						"	"
		3	20	180		9	<0.5		<3				Network Pol. Polyfine
		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	20	180		9	<0.5		<3				Network Pol. Polyfine
		10	60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
		10	60	180		4	0.5-5						Network Pol. Polyfine
		30	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		30	20	180		9	<0.5		<3				Network Pol. Polyfine
		30	21			8						satisfactory resistance	Solvay Fortilene
		30	23	365		8	0	0.2				yellowed	Eastman Tenite 4231; 50.8x3.2 mm discs
		30	60			5						some attack	Solvay Fortilene
		30	100	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
		30	100	180		1						no chemical resistance	Network Pol. Polyfine
		90	21			5						some attack	Solvay Fortilene
		90	60			5						"	"
Hydrogen Sulfide		90	100			2						unsatisfactory resistance	"
			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Hydroiodic Acid			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			60			2						"	"
Hydroquinone			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Igepal			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Inks			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Iodine	tincture of iodine dry moist dry moist dry		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			21			2						unsatisfactory resistance	"
			23			8						no significant effect	Phillips Marlex
			23			4						oxidizing agent	"
			60			8						satisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elon-gation		
Isooctane			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Isopropyl Alcohol	isopropanol		20	30		9						negligible effect	“
	“		20	180		9	<0.5		<3				Network Pol. Polyfine
	“		21			8						satisfactory resistance	Solvay Fortilene
	“		23			8						no significant effect	Phillips Marlex
Isopropyl Alcohol	isopropanol		60			8						satisfactory resistance	Solvay Fortilene
	“		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9	<.5		<3				Network Pol. Polyfine
Jet Aircraft Fuels	JP 4 and JP 5		21			5						some attack	Solvay Fortilene
			60		2						unsatisfactory resistance	“	
Kerosine			21			5						some attack	“
			23			7						no signif. effect	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
Ketones			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Lactic Acid		20	20	30		9						“	“
		20	20	180		9	<0.5		<3				Network Pol. Polyfine
		20	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	60	180		9	<.5		<3				Network Pol. Polyfine
		21				8						satisfactory resistance	Solvay Fortilene
		23				8						no significant effect	Phillips Marlex
		60				8						satisfactory resistance	Solvay Fortilene
Lanolin		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		21			8						satisfactory resistance	Solvay Fortilene	
		60			8						“	“	
		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
Lauric Acid		21			8						satisfactory resistance	Solvay Fortilene	
		23			8						no significant effect	Phillips Marlex	
		60			8						satisfactory resistance	Solvay Fortilene	
Lead Acetate	saturated	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		21			8						satisfactory resistance	Solvay Fortilene	
		23			8						no significant effect	Phillips Marlex	
	saturated	60			8						satisfactory resistance	Solvay Fortilene	
		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		100			8						satisfactory resistance	Solvay Fortilene	
Lemon Oil		21			5						some attack	“	
		23			5						may cause soft./ swell.	Phillips Marlex	
Lestoil		2	23	7	0.25%	3				60			LNP ; 30% gl.fib.
		2	23	7		2				52			“
Ligroin			23			5						may cause soft./ swell.	Phillips Marlex
Linseed Oil		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		21			8						satisfactory resistance	Solvay Fortilene	
		23			8						no significant effect	Phillips Marlex	
		23	7	0.25%	9				95		LNP ; 30% gl.fib.	“	
		23	7		9				98		“	“	
		60			8						satisfactory resistance	Solvay Fortilene	
		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		81	3		7				88		LNP ; 30% gl.fib.	“	
Lubricating Oils		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		20	180		9	<0.5		<3				Network Pol. Polyfine	
		21			8						satisfactory resistance	Solvay Fortilene	
		60			5						some attack	“	
		60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens	
Magenta Dye	aqueous		20	30		9						negligible effect	“
	“		60	30		7						neglible effect, some stain.	“
Magnesium Carbonate	saturated	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		21			8						satisfactory resistance	Solvay Fortilene	
		23			8						no significant effect	Phillips Marlex	
		60			8						satisfactory resistance	Solvay Fortilene	
	saturated	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
		100			8						satisfactory resistance	Solvay Fortilene	

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note									
							Weight	Thick-ness	Volume	Tensile Strength	Elon-gation											
Magnesium Chloride	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
	saturated		60	30		8						Solvay Fortilene										
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			100			5						some attack	Solvay Fortilene									
Magnesium Hydroxide	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
	saturated		60	30		8						Solvay Fortilene										
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			100			8						satisfactory resistance	Solvay Fortilene									
Magnesium Nitrate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
	saturated		60	30		8						Solvay Fortilene										
			60			9						satisfactory resistance	Solvay Fortilene									
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
Magnesium Sulfate	saturated solution		20	30		9						“	“									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
	saturated solution		60	30		8						Solvay Fortilene										
			60			9						satisfactory resistance	Solvay Fortilene									
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
Magnesium Sulfite	saturated		20	30		9						“	“									
			21			8						satisfactory resistance	Solvay Fortilene									
	saturated		60	30		8						“	“									
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
Malic Acid			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
			60			5						some attack	Solvay Fortilene									
Meat Juices			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			60	30		9						“	“									
Mercuric Chloride		40	20	30		9							“	“								
		40	60	30		9							“	“								
		21				8							satisfactory resistance	Solvay Fortilene								
		23				8							no significant effect	Phillips Marlex								
		60				8							satisfactory resistance	Solvay Fortilene								
Mercuric Cyanide	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
	saturated		60	30		8						Solvay Fortilene										
			60			9						satisfactory resistance	Solvay Fortilene									
			60			9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
Mercuric Nitrate			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
			60			8						satisfactory resistance	Solvay Fortilene									
Mercurous Nitrate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens									
	“		60	30		9						“	“									
Mercury			20	30		9						“	“									
			21			8						satisfactory resistance	Solvay Fortilene									
			23			8						no significant effect	Phillips Marlex									
			saturated	60		30						8	Solvay Fortilene									
				60								9	satisfactory resistance	Solvay Fortilene								
Merthiolate	tincture		21			8						satisfactory resistance	Solvay Fortilene									
	“		60			8						“	“									
Methane			21			8						“	“									
			60			8						“	“									
Methyl Alcohol		5	23	365		9	0	0.3					no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs								
			20	30		9							negligible effect	Himont Pro-Fax; 76x0.64 mm specimens								
			20	180		9							<0.5	<3	Network Pol. Polyfine							
			21			8							satisfactory resistance	Solvay Fortilene								
			23			8							no significant effect	Phillips Marlex								
			23	7		0.25%							9		94	100	100		no visible change	Eastman Ektar FB PG001; 10% gl.fib.		
			23	7									9	100								
			23	28		9								87	0.4	0.5						
			23	365		8							slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs								
			60			8							satisfactory resistance	Solvay Fortilene								
			60	30		9							satisfactory resistance	Solvay Fortilene								
			60	180		9							<.5	<3	Himont Pro-Fax; 76x0.64 mm specimens							
			65	3		6									83	Network Pol. Polyfine						
Methyl Cellosolve			21			8							satisfactory resistance	Solvay Fortilene								
			23			6							no visible change	Eastman Ektar FB PG001; 10% gl.fib.								

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Methyl Chloride			21			2						unsatisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
Methyl Ethyl Ketone			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60			7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
Methyl Isobutyl Carbinol			23	28		6				95	300	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
Methyl Isobutyl Ketone			21	28		8				71	700	satisfactory resistance	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			23			4						no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			60			8						satisfactory resistance	Solvay Fortilene
Methyl Sulfuric Acid			21			8						"	"
			60			8						"	"
Methylene Chloride			20	30		9	>5		>8			negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		5							Network Pol. Polyfine
			21			8						satisfactory resistance	Solvay Fortilene
			22	28		1							Himont ; flame retard.
			23			5						may cause soft./ swell.	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	180		5							Network Pol. Polyfine
			100	180		5							"
Milk	and its products		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
Milk	and its products		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100	30		9						"	"
Mineral Oils			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			7						no signif. effect	Phillips Marlex
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
Mineral Spirits			21			8						satisfactory resistance	Solvay Fortilene
			23			7						no signif. effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Molasses			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Motor Oils	10W-30		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23	7	0.25%	8							LNP ; 30% gl.fib.
			23	7		8							"
			23	28		9						no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			23	30		9							Phillips Marlex
			23	365		9						no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
			81	3		6							LNP ; 30% gl.fib.
Naphtha			21			8						satisfactory resistance	Solvay Fortilene
			23			7						no signif. effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
Naphthalene			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
			100	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Nickel Chloride	saturated		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Nickel Nitrate	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Nickel Sulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Nitric Acid		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	20	180		9	<0.5		<3			satisfactory resistance	Network Pol. Polyfine
		10	21			8							Solvay Fortilene
		10	60			8						"	"
		10	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	60	180		9	<.5		<3			satisfactory resistance	Network Pol. Polyfine
		10	100			8						Solvay Fortilene	
		10	100	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	100	180		4	0.5-5					Network Pol. Polyfine	
		<50	23			8						Phillips Marlex	
	with hydrochloric acid	50	20	30		5						no significant effect	Himont Pro-Fax; 76x0.64 mm specimens
	with sulfuric acid	50	20	30		4						limited absorp./attack; poss. stress crack agent	"
	"	50	21			2						ext. absorp./perm.; poss. stress crack agent	
		50	23	30		9	0			96		unsatisfactory resistance	Solvay Fortilene
		50	80	30		1						Phillips Marlex	
	with hydrochloric acid	50	80	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
	with sulfuric acid	50	80	30		1						"	"
		60	20	30		9						negligible effect	"
		60	80	30		1						dissolves/disint.	"
		70	20	30		4						ext. absorp./perm.; poss. stress crack agent	"
		70	20	30		9	<0.5		<3			dissolves/disint.	Network Pol. Polyfine
		70	60	30		1						Himont Pro-Fax; 76x0.64 mm specimens	
	fuming		20	30		1						"	"
	concentrated		21			5						some attack	Solvay Fortilene
	fuming		21			2						unsatisfactory resistance	"
	"		23			4						oxidizing agent	Phillips Marlex
	concentrated		23	365		6	1	0.3				yellowed	Eastman Tenite 4231; 50.8x3.2 mm discs
	"		60			2						unsatisfactory resistance	Solvay Fortilene
	fuming		60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
	"		100	30		1						"	"
Nitrobenzene			20	30		9						negligible effect	"
			20	180		9	<0.5		<3			satisfactory resistance	Network Pol. Polyfine
			21			8						Solvay Fortilene	
			23			5						may cause soft./swell.	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Nitromethane			23	28		9				99	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Nitrous Acid			21			5						some attack	Solvay Fortilene
			60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
Oleic Acid			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			23	365		9	0.2	0.3				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						satisfactory resistance	Solvay Fortilene
Oleum			21			2						unsatisfactory resistance	"
			100	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
Olive Oil			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9	<0.5		<3			satisfactory resistance	Network Pol. Polyfine
			21			8						Solvay Fortilene	
			23			8						no significant effect	Phillips Marlex
			23	365		9	0	0.5				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		9	<.5		<3			Network Pol. Polyfine	
Oxalic Acid		50	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		50	60	30		7						suitable for most applic.	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Oxygen			21 23 60			2 4 2						unsatisfactory resistance oxidizing agent unsatisfactory resistance	" Phillips Marlex Solvay Fortilene
Ozone			21 23 60			2 4 2						" oxidizing agent unsatisfactory resistance	" Phillips Marlex Solvay Fortilene
Paradichlorobenzene			21 60			8 8						satisfactory resistance "	" "
Paraffin	white paraffin		20 20 21 60 60 80	30 30 30 30		9 9 8 8 7 7						negligible effect " satisfactory resistance " suitable for most applic. "	Himont Pro-Fax; 76x0.64 mm specimens " Solvay Fortilene " Himont Pro-Fax; 76x0.64 mm specimens "
Peanut Oil			21 23 60			8 8 8						satisfactory resistance no significant effect satisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Perchloric Acid			23			8						no significant effect	Phillips Marlex
Perchloroethylene			21 23 60			2 5 2						unsatisfactory resistance may cause soft./ swell. unsatisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Petroleum Ether			20 23 60	30 30		4 5 4						ext. absorp./perm.; short use maybe OK may cause soft./ swell. ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens Phillips Marlex Himont Pro-Fax; 76x0.64 mm specimens
Petroleum Spirits	white spirits "		20 60	30 30		7 4						suitable for most applic. ext. absorp./perm.; short use maybe OK	" "
Phenoil		10 10 10	21 60 100			8 8 5						satisfactory resistance " some attack	Solvay Fortilene " "
Phenol		5	23 20 23 60	365 30 30		9 9 8 9	0.1	0.1				no change in appearance negligible effect no significant effect negligible effect	Eastman Tenite 4231; 50.8x3.2 mm discs Himont Pro-Fax; 76x0.64 mm specimens Phillips Marlex Himont Pro-Fax; 76x0.64 mm specimens
Phosgene	gas liquid		21 21			2 2						unsatisfactory resistance "	Solvay Fortilene "
Phosgene	gas liquid		23 60 60			5 2 2						may cause soft./ swell. unsatisfactory resistance "	Phillips Marlex Solvay Fortilene "
Phosphoric Acid		30 30 30 85 85 85 85 85 85 95 95	21 60 100 20 21 60 60 100 100 20 60 23 23	 180 180 180 30 30 365		8 8 5 9 8 8 9 5 9 9 9 8 9	 0.5 0.5 0.5 0	 -0.2			satisfactory resistance " some attack satisfactory resistance " " some attack " negligible effect " no significant effect no change in appearance	" " " Network Pol. Polyfine Solvay Fortilene " Network Pol. Polyfine Solvay Fortilene Network Pol. Polyfine Himont Pro-Fax; 76x0.64 mm specimens " Phillips Marlex Eastman Tenite 4231; 50.8x3.2 mm discs	
Phosphorous			21			8						satisfactory resistance	Solvay Fortilene
Photographic Developers			20 60	30 30		9 9						negligible effect "	Himont Pro-Fax; 76x0.64 mm specimens "
Phthalic Acid			21 23			8 8						satisfactory resistance no significant effect	Solvay Fortilene Phillips Marlex
Picric Acid			23			8						"	"

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Plating Solutions	brass		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	cadmium		20	30		9						"	"
	chromium		20	30		9						"	"
	copper		20	30		9						"	"
	gold		20	30		9						"	"
	indium		20	30		9						"	"
	lead		20	30		9						"	"
	nickel		20	30		9						"	"
	rhodium		20	30		9						"	"
	silver		20	30		9						"	"
	tin		20	30		9						"	"
	zinc		20	30		9						"	"
	brass		60	30		9						"	"
	cadmium		60	30		9						"	"
	chromium		60	30		9						"	"
	copper		60	30		9						"	"
	gold		60	30		9						"	"
	indium		60	30		9						"	"
	lead		60	30		9						"	"
	nickel		60	30		9						"	"
	rhodium		60	30		9						"	"
	silver		60	30		9						"	"
	tin		60	30		9						"	"
	zinc		60	30		9						"	"
Polyvinyl Acetate			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Potassium		6	20	180		9	<0.5		<3				Network Pol. Polyfine
		6	60	180		9	<.5		<3			"	"
Potassium Bicarbonate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		60	30		9						"	"
Potassium Borate		1	20	30		9						"	"
		1	60	30		9						"	"
Potassium Bromate		10	20	30		9						"	"
		10	60	30		9						"	"
Potassium Bromide	saturated solution		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated solution		60			8						Solvay Fortilene	
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Potassium Carbonate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Potassium Chlorate	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated solution		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene
Potassium Chloride	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated solution		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene
Potassium Chromate		40	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		40	60	30		9						"	"
Potassium Cyanide	saturated		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Potassium Dichromate		10	23	365		9	0	0.3				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
		40	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		40	60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			8						"	"
Potassium Ferricyanide			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Potassium Ferrocyanide			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
Potassium Ferrocyanide			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Potassium Fluoride			20	30		9						"	"
			60	30		9						"	"
Potassium Hydroxide		10	20	30		9						"	"
		10	60	30		9						"	"
		10	100	30		9						"	"
		50	20	30		9						"	"
		50	60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			8						"	"
Potassium Iodide			23			8						no significant effect	Phillips Marlex
Potassium Nitrate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Potassium Perborate	"		20	30		9						"	"
	"		60	30		9						"	"
Potassium Perchlorate		10	20	30		9						"	"
		10	60	30		9						"	"
Potassium Permanganate		20	20	30		9						"	"
		20	60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			5						some attack	Solvay Fortilene
Potassium Sulfate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
	saturated		60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
			100			8						satisfactory resistance	Solvay Fortilene
Potassium Sulfide			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Potassium Sulfite			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Propyl Alcohol	1-propanol		20	30		9						"	"
	"		21			8						satisfactory resistance	Solvay Fortilene
	"		23			8						no significant effect	Phillips Marlex
	"		60			8						satisfactory resistance	Solvay Fortilene
	"		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Pyridine			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		9	<0.5		<3			Network Pol. Polyfine	
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Sea Water	in sand; salinity: 27%		15-26	90		6	0.08			101	263		Himont ; 1.2 mm thick sheet
	"		15-26	90		8	0.04			98	79		Himont ; 1.2 mm sheet; low MI
	"		15-26	90		7	0.08			98	139		"
Shellac			23			8						no significant effect	Phillips Marlex
Silicone Oils			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Silver Cyanide			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
Silver Nitrate			21			8						"	"
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			8						"	"
Soap	concentrated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	solutions		60	30		9						"	"
Sodium Acetate			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Benzoate			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
			100			8						"	"
Sodium Bicarbonate	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Bisulfate	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Bisulfite	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Borate			20	30		9						"	"
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Bromide	sodium bromide oil		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
Sodium Bromide			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	sodium bromide oil		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Carbonate		2	23	365		8	0	-0.2				very yellow	Eastman Tenite 4231; 50.8x3.2 mm discs
	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
Sodium Chlorate	saturated solution		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			5						some attack	Solvay Fortilene

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Sodium Chloride	saturated	10	23	365		9	0	-0.2				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
			20	30		9					negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
			21			8					satisfactory resistance	Solvay Fortilene	
			23			8					no significant effect	Phillips Marlex	
	saturated		60			8					satisfactory resistance	Solvay Fortilene	
			60	30		9					negligible effect	Himont Pro-Fax; 76x0.64 mm specimens	
	saturated	100		5						some attack	Solvay Fortilene		
		100	30		9					negligible effect	Himont Pro-Fax; 76x0.64 mm specimens		
Sodium Chlorite		2	20	30		9						"	"
		2	80	30		9						"	"
		5	20	30		9						"	"
		5	80	30		9						"	"
		10	20	30		9						"	"
		10	80	30		9						"	"
		20	20	30		9						"	"
		20	80	30		9						"	"
Sodium Cyanide	saturated		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Dichromate	"		20	30		9						"	"
	"		60	30		9						"	"
Sodium Ferricyanide	"		20	30		9						"	"
	"		60	30		9						"	"
Sodium Fluoride			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Hydroxide		1	23	365		9	0	0.6				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	23	28		6				95	275	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
		10	23	365		9	0	0.1				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
	Sodium Hydroxide		10	60	30		9						negligible effect
10			100	30		9						"	"
50			20	30		9						"	"
50			60	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
concentrated			23			8						no significant effect	Phillips Marlex
			23	30		9	0			95		satisfactory resistance	Solvay Fortilene
			60			8						"	"
			100			8						"	"
Sodium Hypochlorite		20	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		20	20	180		9	<0.5		<3			Network Pol. Polyfine	
		20	60	30		7						Himont Pro-Fax; 76x0.64 mm specimens	
		20	60	180		4	0.5-5					Network Pol. Polyfine	
		20	100	30		7						Himont Pro-Fax; 76x0.64 mm specimens	
		23	365		9	0	-0.3					no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
Sodium Metaphosphate			23			8						no significant effect	Phillips Marlex
Sodium Nitrate			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Nitrite			20	30		9						"	"
			60	30		9						"	"
Sodium Perborate			23			8						no significant effect	Phillips Marlex
Sodium Phosphate			23			8						"	"
Sodium Silicate			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Sulfate	saturated		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Sulfide		25	20	30		9						"	"
		25	60	30		9						"	"
			23			8						no significant effect	Phillips Marlex

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Sodium Sulfite	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sodium Thiosulfate			23			8						no significant effect	Phillips Marlex
Soybean Oil			23			8						"	"
Stannic Chloride	saturated		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Stannous Chloride	"		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Starch			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Stearic Acid			23			8						no significant effect	Phillips Marlex
Succinic Acid			23			8						"	"
Sucrose		20	21			8						satisfactory resistance	Solvay Fortilene
		20	60			8						"	"
			23			8						no significant effect	Phillips Marlex
Sugars	and syrups		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Sulfamic Acid			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			80	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sulfur			20	30		9						"	"
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Sulfur Chloride			23			8						no significant effect	Phillips Marlex
Sulfur Dioxide			23			8						"	"
Sulfuric Acid		2	20	180		9	<0.5		<3				Network Pol. Polyfine
		2	60	180		9	<.5		<3				"
		2	100	180		9	<.5		<3				"
		3	23			8						no significant effect	Phillips Marlex
		3	23	365		9	0	0				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
		10	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	20	180		9	<0.5		<3				Network Pol. Polyfine
		10	21			8						satisfactory resistance	Solvay Fortilene
		10	23			8						no significant effect	Phillips Marlex
		10	23	7	0.25%	9				94		LNP ; 30% gl.fib.	"
		10	23	7		9				94			"
		10	60			8						satisfactory resistance	Solvay Fortilene
		10	60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	60	180		9	<.5		<3				Network Pol. Polyfine
		10	100			8						satisfactory resistance	Solvay Fortilene
		10	100	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
		10	100	180		9	<.5		<3				Network Pol. Polyfine
Sulfuric Acid		20	23	28		9				97	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.
		30	23			8						no significant effect	Phillips Marlex
		30	23	365		9	0	-0.2				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
		50	20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	with nitric acid	50	20	30		4						ext. absorp./perm.; poss. stress crack agent	"
		50	21			8						satisfactory resistance	Solvay Fortilene
		50	23			8						no significant effect	Phillips Marlex
		50	60			8						satisfactory resistance	Solvay Fortilene
	with nitric acid	50	60	30		7						suitable for most applic.	Himont Pro-Fax; 76x0.64 mm specimens
		50	80	30		1						dissolves/disint.	"
		60	20	30		9						negligible effect	"
		60	80	30		7						suitable for most applic.	"

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Sulfuric Acid	with chromic acid concentrated fuming, 20% oleum " concentrated concentrated with chromic acid concentrated	50-95	23			7						no signif. effect	Phillips Marlex
		96-98	23			7						"	"
		98	20	30		4						ext. absorp./perm.; poss. stress crack agent	Himont Pro-Fax; 76x0.64 mm specimens
		98	20	180		9	<0.5		<3				Network Pol. Polyfine
		98	23	30		9	0			97			Phillips Marlex
		98	60	180		5	>5		>8				Network Pol. Polyfine
		98	100	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
		98	100	180		1						no chemical resistance	Network Pol. Polyfine
			20	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			21			2						unsatisfactory resistance	"
			23			4						oxidizing agent	Phillips Marlex
			23	365		8	0	0.2				stained	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60			5						some attack	"
			60	30		1						dissolves/disint.	Himont Pro-Fax; 76x0.64 mm specimens
			100			2						unsatisfactory resistance	Solvay Fortilene
Sulfurous Acid			23			8						no significant effect	Phillips Marlex
Syrups	and sugars		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60	30		9						"	"
Tallow			20	30		9						"	"
			60	30		9						"	"
Tannic Acid	10	10	21			8						satisfactory resistance	Solvay Fortilene
		10	60			8						"	"
			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			23			8						no significant effect	Phillips Marlex
Tartaric Acid	10		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	30		9						"	"
			23			8						no significant effect	Phillips Marlex
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			20	30		9						"	"
			23			8						no significant effect	Phillips Marlex
Tetrahydrofuran			20	30		4						ext. absorp./perm.; short use maybe OK	"
			20	180		5	>5		>8				Network Pol. Polyfine
			21			8						satisfactory resistance	Solvay Fortilene
			23			7						no signif. effect	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		5	>5		>8				Network Pol. Polyfine
			100			5						some attack	Solvay Fortilene
			100	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			100	180		5	>5		>8				Network Pol. Polyfine
Tetralin			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			20	180		5	>5		>8				Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			23			5						may cause soft./ swell.	Phillips Marlex
			60			5						some attack	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Tetralin			60	180		5	>5		>8			some attack	Network Pol. Polyfine
			100			5						ext. absorp./perm.; short use maybe OK	Solvay Fortilene
			100	30		4							Himont Pro-Fax; 76x0.64 mm specimens
			100	180		5	>5		>8				Network Pol. Polyfine
Toluene			20	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			21			2						unsatisfactory resistance	Solvay Fortilene
			23	28		4				56	625		Eastman Ektar FB PG001; 10% gl.fib.
			23	30		2	10			71		no visible change	Phillips Marlex
			23	365		3	12.8	3.6				swelled and slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Transformer Oils			20	30		9						negligible effect	"
			23			7						no signif. effect	Phillips Marlex
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
Transmission Fluid			23	28		9				96	100	no visible change	Eastman Ektar FB PG001; 10% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elon-gation		
Tributyl Phosphate			21 23 60			8 8 5						satisfactory resistance no significant effect some attack	Solvay Fortilene Phillips Marlex Solvay Fortilene
Trichloroacetic Acid			10 10 10 10 10	20 20 60 60 100	30 180 30 180 180	9 9 9 9 9	<0.5		<3			negligible effect negligible effect	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine "
2 N			21 23 60			8 8 8	<.5		<3			satisfactory resistance no significant effect satisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Trichloroethylene			20 20 21 23 60 60 60 100 100	30 180 30 180 30 180		4 5 2 5 2 4 5 4 5	>5		>8			ext. absorp./perm.; short use maybe OK unsatisfactory resistance may cause soft./ swell. unsatisfactory resistance ext. absorp./perm.; short use maybe OK ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Solvay Fortilene Phillips Marlex Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine Himont Pro-Fax; 76x0.64 mm specimens Network Pol. Polyfine
Tricresyl Phosphate			21 23 60			8 8 8						satisfactory resistance no significant effect satisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Triethanolamine			20 21 60 80	30 30		9 5 5 9						negligible effect some attack " negligible effect	Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene " Himont Pro-Fax; 76x0.64 mm specimens
Triethyl Phosphate			23	365		9	0.1	0.2				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
Trisodium Phosphate			21 23 60			8 8 8						satisfactory resistance no significant effect satisfactory resistance	Solvay Fortilene Phillips Marlex Solvay Fortilene
Turpentine			20 21 23 23 23 60 60 100 100	30 30 365 30 30		4 8 5 2 2 5 4 5 4	13 14.2	5	64			ext. absorp./perm.; short use maybe OK satisfactory resistance may cause soft./ swell. swelled and bleached some attack ext. absorp./perm.; short use maybe OK some attack ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene Phillips Marlex " Eastman Tenite 4231; 50.8x3.2 mm discs Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens
Urea			20 21 23 60 60	30 30		9 8 8 8 9						negligible effect satisfactory resistance no significant effect satisfactory resistance negligible effect	" Solvay Fortilene Phillips Marlex Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens
Urine			20 21 60 60	30 30		9 8 8 9						" satisfactory resistance " negligible effect	" Solvay Fortilene " Himont Pro-Fax; 76x0.64 mm specimens
Vegetable Oils			23	365		9	0	-0.2				no change in appearance	Eastman Tenite 4231; 50.8x3.2 mm discs
Vinegar			23			8						no significant effect	Phillips Marlex
Water			distilled hard vapor 21 23 23 60 60 60 60 60 60	20 20 20 30 28 365 30 30 30 30	30 30 30 30	9 9 9 8 6 9 8 9 9 9	0	0.2	95	250		negligible effect " " satisfactory resistance no visible change no change in appearance satisfactory resistance negligible effect " " "	Himont Pro-Fax; 76x0.64 mm specimens " " Solvay Fortilene Eastman Ektar FB PG001; 10% gl.fib. Eastman Tenite 4231; 50.8x3.2 mm discs Solvay Fortilene Himont Pro-Fax; 76x0.64 mm specimens " " "

Reagent	Reagent Note	Conc. (%)	Temp (°C)	Time (days)	Load	PDL Rating	% Change			% Retained		Resistance Note	Material Note
							Weight	Thick-ness	Volume	Tensile Strength	Elongation		
Water			100			5						some attack	Solvay Fortilene
	boiling water		100	1		7	1.9			94.5			Himont Pro-Fax PD-701; 10% cel.fib.
	"		100	1		6	1.2						"
	"		100	1		5	3.5			88.9			Himont Pro-Fax PD-701; 20% cel.fib.
	"		100	1		4	3						"
	"		100	1		4	5.3			78.4			Himont Pro-Fax PD-701; 30% cel.fib.
	"		100	1		2	4.4						"
	"		100	1		3	7.3			70.3			Himont Pro-Fax PD-701; 40% cel.fib.
	"		100	1		1	6.3						"
	"		100	1		7				97.8			Himont Pro-Fax PD-701; 10% cel.fib.
	"		100	1		5				89			Himont Pro-Fax PD-701; 20% cel.fib.
	"		100	1		4				72			Himont Pro-Fax PD-701; 30% cel.fib.
	"		100	1		4				75.2			Himont Pro-Fax PD-701; 40% cel.fib.
	water changed weekly		100	4.2		8				92			30% gl.fib.
Water	distilled		100	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	hard		100	30		9						"	"
	vapor		100	30		9						"	"
	water changed weekly		100	41.7		7				87			30% gl.fib.
	"		100	625		5				77			"
	"		100	208		6				81			"
	"		100	417		5				79			"
Waxes	paraffin wax		20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
	"		60	30		9						"	"
Whiskey			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			100			8						satisfactory resistance	Solvay Fortilene
			100	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Wines			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			60			9						"	"
Xylene			20	30		4						ext. absorp./perm.; short use maybe OK	"
			20	180		5	>5		>8				Network Pol. Polyfine
			21			5						some attack	Solvay Fortilene
			21			8						satisfactory resistance	"
			23			5						may cause soft./ swell.	Phillips Marlex
			23	365		3	12.7	3.7				swelled and slightly bleached	Eastman Tenite 4231; 50.8x3.2 mm discs
			60			2						unsatisfactory resistance	Solvay Fortilene
			60	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			60	180		5	>5		>8				Network Pol. Polyfine
			100	30		4						ext. absorp./perm.; short use maybe OK	Himont Pro-Fax; 76x0.64 mm specimens
			100	180		5	>5		>8				Network Pol. Polyfine
			100			9						"	"
Yeast			20	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Zinc Chloride	saturated solution		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated solution		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Zinc Oxide			20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			60			8						"	"
			60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens
Zinc Sulfate	saturated		20	30		9						"	"
			21			8						satisfactory resistance	Solvay Fortilene
			23			8						no significant effect	Phillips Marlex
			60			8						satisfactory resistance	Solvay Fortilene
	saturated		60	30		9						negligible effect	Himont Pro-Fax; 76x0.64 mm specimens

Glossary of Terms

2-hydroxybenzophenone An aromatic ketone, $C_6H_5COC_6H_4OH$, used as UV absorber in plastics. A solid at room temperature, insoluble in water but soluble in alcohols.

ABS See acrylonitrile butadiene styrene polymer.

accelerator A chemical substance that accelerates chemical, photochemical, biochemical, etc. reaction or process, such as crosslinking or degradation of polymers, that is triggered and/or sustained by another substance, such as curing agent or catalyst, or environmental factor, such as heat, radiation or a microorganism. Also called promoter, cocatalyst.

acetone A volatile, colorless, highly flammable liquid with molecular formula CH_3COCH_3 . Acetone has autoignition temperature $537^\circ C$, mixes readily with water and some other solvents and is moderately toxic. Acetone dissolves most thermoplastics and some thermosets. Used as organic synthesis intermediate, e.g., in the manufacture of bisphenol A and antioxidants, as solvent in paints and acetate fiber spinning and for cleaning of electronic parts. Also called dimethyl ketone.

acrylate resin See *acrylic resin*.

acrylic epoxy resin See *vinyl ester resin*.

acrylic resin The class of thermoplastics comprised of homopolymers and copolymers of alkyl (meth) acrylates. The most common monomers used are methyl and ethyl (meth)acrylates; the comonomers include other unsaturated monomers. The acrylic resins offer excellent optical clarity, weatherability and resistance to sunlight, outstanding surface hardness, good chemical resistance, rigidity, good impact strength, excellent dimensional stability, and low mold shrinkage. They have poor solvent resistance, are subject to stress cracking, are combustible, and have low flexibility and thermal stability. The acrylic resins can be cast in sheets, rods, or tubing; extruded into sheets or profiles; injection molded; thermoformed; and coated. The applications include transparent items such as lenses, automotive trim, household items, light fixtures, conformed coatings on printed circuit boards, and medical devices. Also called polyacrylate, acrylate resin.

acrylonitrile butadiene styrene polymer ABS resins are thermoplastics comprised of a mixture of styrene-acrylonitrile copolymer (SAN) and SAN-grafted butadiene rubber. They have high impact resistance, toughness, rigidity and processability, but low dielectric strength, continuous service temperature, and elongation. Outdoor use requires protective coatings in some cases. Plating grades provide excellent adhesion to metals. Processed by extrusion, blow molding, thermoforming, calendaring and injection molding. Used in household appliances, tools, nonfood packaging, business machinery, interior automotive parts, extruded sheet, pipe and pipe fittings. Also called ABS.

acrylonitrile copolymer Acrylonitrile copolymers are thermoplastics prepared by copolymerization of acrylonitrile with minor amounts of other unsaturated mono-

mers. The class of acrylonitrile copolymers include ASA, ABS, SAN, and nitrile resins. In a narrower sense the term acrylonitrile copolymers is often used to denote (high) nitrile (barrier) resins. These resins have good gas barrier properties, chemical resistance, and taste and odor retention properties. These resins have moderately high tensile properties and good impact properties when rubber modified or oriented. Processed by extrusion, injection molding, and thermoforming. Used mainly in food and nonfood packaging. FDA approved for direct contact with food with some limitations.

activation energy An excess energy that must be added to an atomic or molecular system to allow a process, such as diffusion or chemical reaction, to proceed.

adherend A body held to another body, usually by an adhesive or solvent. A part or detail being prepared for bonding.

adhesion promoter A coating applied to a substrate prior to adhesive application, in order to improve adhesion of the material, such as a plastic. Also called primer.

adhesive A material, usually polymeric, capable of forming permanent or temporary surface bonds with another material as is or after processing such as curing. Used for bonding and joining. Many classes of adhesives include hot-melt, pressure-sensitive, contact, UV cured, emulsion, etc.

adhesive abrasion In adhesive bonding, a surface preparation technique in which the part surface is mechanically abraded in the presence of liquid adhesive. Abraded, adhesive-coated adherends are then mated, and adhesive is allowed to cure. It is speculated that abrasion in the presence of adhesive creates free radicals that react directly with the adhesive; when abrasion is performed in the absence of adhesive, the generated free radicals are scavenged by oxygen in air before adhesive is applied. Adhesive abrasion is commonly used on fluorocarbons; bond strengths of Teflon (PTFE) were increased about 700% using this technique.

adhesive bonding A method of joining two plastics or other materials in which an adhesive is applied to the part surfaces. Bonding occurs through mechanical or chemical interfacial forces between the adhesive and adherend and/or by molecular interlocking. Surface preparation of the adherends and curing of the adhesive may be required.

adhesive failure Failure of an adhesive bond at the adhesive-adherend interface. An example is an adhesive failure that leaves adhesive all on one adherend, with none on the other adherend. Adhesive failure is less desirable than cohesive failure because it is indicative of a joint with lower adhesive strength. See also cohesive failure.

adsorption Retention of a substance molecule on the surface of a solid or liquid. Also called physical adsorption.

aging See *conventional aging*.

air attenuated fiber process See *melt blown fiber process*, *spun bond fiber process*.

aliphatic compound An open chain compound or ring structure with no π -electron system (no delocalized electrons within the ring). See also aromatic compound.

alkyl group A hydrocarbon functional group that results from the removal of one hydrogen from the original hydrocarbon: CH_3 - (methyl) is derived from CH_4 (methane), CH_3CH_2 - (ethyl) from CH_3CH_3 (ethane), etc.

alpha cellulose See *cellulose*.

amideimide resin See *polyimide*.

amorphous nylon Amorphous nylons are transparent products that typically involve rings in copolymer chains. One amorphous nylon involves 2,4,4- and 2,2,4-trimethylhexamethylene diamine and terephthalic acid.

amorphous polymer Amorphous polymers are polymers having noncrystalline or amorphous supramolecular structure or morphology. Amorphous polymers may have some molecular order but usually are substantially less ordered than crystalline polymers and subsequently have inferior mechanical properties.

amplitude The maximum displacement of a particle measured from its equilibrium position.

anisotropic Exhibiting different properties when tested along axes in different directions.

annealing A process in which a material, such as plastic, metal, or glass, is heated then cooled slowly. In plastics and metals, it is used to reduce stresses formed during fabrication. The plastic is heated to a temperature at which the molecules have enough mobility to allow them to reorient to a configuration with less residual stress. Semicrystalline polymers are heated to a temperature at which retarded crystallization or recrystallization can occur.

antimony pentoxide (SbO_5) A white or yellowish powder that melts at 450°C (842°F). Loses oxygen above 300°C (572°F). Soluble in strong bases, forming antimonates; slightly soluble in water; insoluble in acids except for concentrated hydrochloric acid. Derived by reaction of concentrated nitric acid with the metal or trioxide. Used as a flame retardant for textiles and in the preparation of antimonates and other antimony compounds. Also called antimonian anhydride, antimonian acid, stibic anhydride.

antimony trioxide (Sb_2O_3) A white, odorless, crystalline powder that melts at 655°C (1211°F). Soluble in concentrated hydrochloric and sulfuric acids and strong bases; insoluble in water. Amphoteric, a suspected carcinogen. Derived by reaction of ammonium hydroxide with antimony chloride, combustion of antimony in air, or directly from low-grade ores. Used in flameproofing textiles, paper, and plastics, especially polyvinyl chloride; glass decolorizer; paint pigments; staining of copper and iron; opacifying ceramics; and as a catalyst or intermediate in organic reactions. Also called antimony white, antimony oxide.

antioxidant A chemical substance capable of inhibiting oxidation or oxidative degradation of another substance such as plastic in which it is incorporated. Antioxidants act by terminating chain-propagating free radicals or by decomposing peroxides, formed during oxidation, into stable products. The first group of antioxidants include

hindered phenols and amines; the second — sulfur compounds such as thiols.

aromatic compound A compound that contains one or more rings with conjugated π -electron systems, in which the electrons are delocalized throughout the ring structure. Generally refers to benzene and compounds that resemble benzene in chemical behavior.

asbestos Asbestos fillers are made from fibrous mineral silicates, mostly chrysotile. Used in thermosetting resins and laminates in fibrous form as reinforcements and in thermoplastics such as polyethylene in finer form as a filler. Asbestos fillers resist heat and chemicals, while providing reinforcement, but pose health hazards and therefore their use has been declining.

aseptic In food processing, a process or condition that renders a processed food product essentially free of microorganisms capable of growing in the food in unrefrigerated distribution and storage conditions. In aseptic food packaging, presterilized containers are filled with aseptic foods, then hermetically sealed in a commercially sterile atmosphere.

ASTM D638 An American Society for Testing of Materials (ASTM) standard method for determining tensile strength, elongation and modulus of elasticity of reinforced or unreinforced plastics in the form of sheet, plate, moldings, rigid tubes and rods. Five (I-V) types, depending on dimensions, of dumbbell-shaped specimens with thickness not exceeding 14 mm are specified. Specified speed of testing varies depending on the specimen type and plastic rigidity.

ASTM D1002 An American Society for Testing of Materials (ASTM) standard practice for testing the shear strength of rigid sheet material by tensile loading. Two sections of a rigid sheet material, usually 4 in. in length x 1 in. in width x 0.064 in. in thickness (101.6 x 25 x 1.62 mm) and having suitably treated surfaces, are overlapped 0.5 in. (12.7 mm) and adhesively bonded together in a 0.5 square inch contact area (323 mm²). Both ends are then clamped firmly into the jaws of a tensile testing machine, and the jaws are moved apart at a speed of 0.05 in./min. (1.3 mm/min.) until joint failure occurs. The failing load, in psi (MPa) and mode of failure (adhesive, cohesive, or mixed) is reported. This is the most commonly used shear test for metal-to-metal structural adhesives. Although it is useful for quality control and comparing different adhesives, failure strength values are not useful for engineering design due to the complex stress distribution pattern in the adhesive with this joint configuration. Also called the lap shear test. Also called lap shear test.

ASTM D1761 An American Society for Testing of Materials (ASTM) standard practice for testing the strength and performance of mechanical fasteners in wood. Withdrawal resistance of wood to nails, staples, and screws is measured by recording the maximum load of fasteners withdrawn at a uniform rate of speed by a testing machine. Resistance of nails, staples, and screws to lateral movement is tested by tensile loading. Strength and rigidity of timber joints fastened with bolts or other metal connectors is tested by measuring the deformation of the joint at various intervals of loading. Vertical load capacity

and torsional moment capacity of joist hangers is tested by measuring the amount of slip under load.

ASTM D4501 An American Society for Testing of Materials (ASTM) standard practice for determining the shear strengths of adhesives used to bond rigid materials by the block shear method. Adhesively bonded blocks, plates, or disks, with flash and fillets removed on the loaded side, are mounted into the shear fixture of a testing machine (capacity not less than 44 kN (10,000lbf)). Test specimens can be any size within the limits of the shearing fixture capacity. The shear fixture is mounted into the testing machine in such a way that one adherend is engaged by the holding block and the other by the shearing tool. A crosshead speed of 1.26 mm/min. (0.05 in./min.) is used for testing. The maximum forces sustained by the specimen is recorded. This test is particularly applicable for testing bonds between ceramic, glass, magnet moldings, and plastic parts with one flat face in which machining is difficult or impractical.

atactic A polymeric molecular structure in which atoms are arranged randomly, with no long-range order, along the polymer chain. The irregular structure prevents a high degree of crystallization. See also syndiotactic, isotactic.

average molecular weight See *molecular weight*.

B

bar A metric unit of measurement of pressure equal to 1.0×10^6 dynes/cm² or 1.0×10^5 pascals. It has a dimension of unit of force per unit of area. Used to denote the pressure of gases, vapors and liquids.

barite See *barium sulfate*.

barium sulfate Barium sulfate is a filler and a white pigment produced by wet or dry of solutions containing barium and sulfate ions. Barium sulfate increases the specific gravity of plastics and imparts dimensional stability, chemical and moisture resistance, thermal conductivity, x-ray opacity, and surface uniformity. As a pigment it shows low tinctorial power. Also called barite.

barrier material Materials such as plastic films, sheeting, wood laminates, particle board, paper, fabrics, etc. with low permeability to gases and vapors. Used in construction as water vapor insulation, food packaging, protective clothing, etc.

base resin melt index See *melt index*.

bending strength See *flexural strength*.

benzene An aromatic hydrocarbon with six-atom carbon ring, C₆H₆. Highly toxic and flammable (autoignition point 562°C). A colorless or yellowish liquid under normal conditions (b.p. 80.1°C), soluble in many organic solvents such as ethanol, acetone, tetrachlorocarbon, etc. Used for synthesis of organic compounds.

biaxial orientation Orientation in which the material is drawn in two directions, usually perpendicular to one another. Commonly used in films and sheets. See also orientation.

bisphenol A epoxy resin See *epoxy resin*.

blister package A type of package in which the product is placed in a small blister formed from a thin plastic sheet; a backing material is then applied to enclose the product.

block copolymer An essentially linear polymer consisting of a small number of repeated sequences of polymeric segments of a different chemical structure. See also random block copolymer, random copolymer, homopolymer

blooming An undesirable cloudy effect or whitish powdery deposit on the surface of a plastic article caused by the exudation of a compounding ingredient such as lubricant, stabilizer, pigment, etc.

blowing agent A compounding agent that forms a gas during polymer processing, resulting in a foamed, porous structure that contains minute cells or bubbles. Blowing agents can be compressed gases or volatile liquids or compounds that decompose at processing temperatures to form a gas. Also called foaming agents.

blow molding A processing method for thermoplastics in which a parison or hollow tube is forced into the shape of the mold cavity by internal air pressure.

blow molding, extrusion A blow molding process in which an extruder feeding a parison head is used to produce the parison as the precursor for the molding process. See also blow molding.

blow molding, injection A blow molding process in which injection molding is used to produce the precursor, called a preform, for the molding process. See also blow molding.

blow molding, stretch A blow molding process in which biaxial orientation is produced in the blown article by axial stretching of the preform before or during blowing. Conventional blow molding processes impart a degree of circumferential orientation due to expansion of the parison into the mold cavity. See also blow molding.

blown film A plastic film produced by extrusion blowing, wherein an extruded plastic tube is continuously inflated by internal air pressure, collapsed by rolls, and wound up. The thickness of the film is controlled by air pressure and rate of extrusion.

booster In ultrasonic welding, a mechanical transformer used to increase or decrease the amplitude of the horn.

boss A hollow or solid projection used for attachment and support of related components. Properly designed bosses and ribs can provide dimensional stability to the part, while reducing material usage and molding cycle time. In mechanical fastening, the hollow projection into which an insert or screw is driven. Solid bosses are also called studs.

breaking elongation See *elongation*.

bulk continuous filament yarn Continuous filament yarn that is texturized or crimped to increase its three-dimensional bulk. Textiles manufactured from bulked continuous filament yarn have improved handling, feel, and elasticity. Yarn is deformed by heating to a temperature slightly below the melting point, using a hot knife edge, turbulent hot air, or steam jets, then cooled, stretched, and allowed to relax.

bursting strength Bursting strength of a material, such as plastic film, is the minimum force per unit area or pres-

sure required to produce rupture. The pressure is applied with a ram or a diaphragm at a controlled rate to a specified area of the material held rigidly and initially flat but free to bulge under the increasing pressure.

Butanone 2- (CH₃COCH₂CH₃) A colorless liquid with an acetone-like odor. Soluble in benzene, alcohol, ether; partially soluble in water; miscible with oils. Its TLV is 200 ppm in air; it is toxic by inhalation and a dangerous fire risk. Explosive limit in air is 2-10%. Derived from sulfuric acid hydrolysis of mixed n-butylenes followed by distillation, by controlled oxidation of butane, or by fermentation. Used as a solvent in nitrocellulose coatings and vinyl films and in paint removers, cements and adhesives, manufacture of smokeless powder, cleaning fluids, and acrylic coatings. Used in printing, and as a reagent for organic synthesis. Also called methyl ethyl ketone, MEK, ethyl methyl ketone. Also called methyl ethyl ketone, MEK.

butt joint A type of edge joint in which the edge faces of the two parts are at right angles to the other faces of the part.

C

calcium carbonate Calcium carbonate is a widely used mineral filler made by wet or dry grinding of limestone or other mineral raw materials or by chemical precipitation. Dry-ground fillers, usually coarser than wet-ground ones, are used in stiff products such as floor tiles and polyester cultured marble. Wet ground fillers are used in flexible products. Precipitated fillers have the smallest particle size and are used in PVC plastisols, PVC pipes, and siding. The fine filler can be surface modified with resins, fatty acids, and calcium stearate to decrease oil absorption for use in plastisols and to improve electrical properties, heat stability, and lubricity during extrusion. Unmodified grades have relatively low cost and provide dimensional stability. Modified grades impart impact strength, and smooth surface. They can be used as film antiblock agents and brighteners.

carbon black Carbon black is a black colloidal carbon filler made by the partial combustion and/or thermal cracking of natural gas, oil, or another hydrocarbon. Depending upon the starting material and the method of manufacture, carbon black can be called acetylene black, channel black, furnace black, etc. For example, channel black is made by impinging gas flames against steel plates or channel irons, from which the deposit is scraped at intervals. The properties and the uses of each carbon black type can also vary. Thus, furnace black comes in high abrasion, fast extrusion, high modulus, general purpose, and semireinforcing grades among others. Carbon black is widely used as a filler and pigment in PVC, phenolic resins, and polyolefins. It increases the resistance to UV light and electrical conductivity and sometimes acts as a crosslinking agent. Also called colloidal carbon.

carbon fiber Carbon fibers are high-performance reinforcement consisting essentially of carbon. They are made by a variety of methods including pyrolysis of cellulosic (e.g., rayon) and acrylic fibers, burning-off binder from a pitch

precursor, and growing single crystals (whiskers) via thermal cracking of hydrocarbon gas. The properties of carbon fibers depend on the morphology of carbon in them and are the highest for crystalline carbon (graphite). These properties include high modulus and tensile strength, high thermal stability, electrical conductivity, chemical resistance, wear resistance, and relatively low weight. Used as continuous or short fibers and in mats in autoclave and die molding, filament winding, injection molding, and pultrusion. Carbon fibers are used at a loading levels of 20-60 vol% or more in both thermosets and thermoplastics such as epoxy resins and ABS. Carbon fibers are often used in combination with other fibers such as glass fibers to make hybrid composites. The end products containing carbon fibers include wheel chairs, tennis racquets, auto parts, machine tools, and support structures in electronic equipment. Also called graphite fiber.

carbon filler Carbon fillers are a family of fillers based on carbon in various forms, such as carbon black and graphite. Used as a black pigment, to improve lubricity, and to increase electrical conductivity of plastics. Also called powdered carbon, carbon powder.

carbon powder *See carbon filler.*

carbon tetrachloride (CCl₄) A colorless liquid with a sweet odor. Miscible with alcohol, ether, chloroform, benzene, solvent naphtha, and most fixed and volatile oils; insoluble in water. Noncombustible. Boils at 76.74°C (170.13°F); freezes at -23°C (-9.4°F); vapor is 5.3 times heavier than air. Its TLV is 5 ppm in air; it is toxic by ingestion, inhalation, and skin absorption. Decomposes to phosgene at high temperatures. Derived by reaction of carbon disulfide and chlorine in the presence of iron or by chlorination of methane or higher hydrocarbons at 250–400°C (752°F). Purified by removal of sulfur chloride using caustic alkali, followed by rectification. Used in metal degreasing, chlorination of organic compounds, the production of semiconductors and solvents (fats, oils, rubber); as a refrigerant and agricultural fumigant. Also called tetrachloromethane, perchloromethane.

cast film Film produced by pouring or spreading resin solution or melt over a suitable temporary substrate, followed by curing via solvent evaporation or melt cooling and removing the cured film from the substrate.

catalyst A substance that increases the rate of a chemical reaction without undergoing any permanent chemical change itself.

cellulose Cellulose is a natural carbohydrate polymer of high molecular weight comprised of long chains of D-glucose units joined together by beta-1,4-glucosidic bonds. It is derived from plants such as cotton and trees. It is used to produce cellulose esters and ethers, i.e., cellulosic plastics, but the largest use is in paper manufacture. Cellulose fillers in a narrow sense are usually made from wood pulp. In a broader sense they may include cotton lint, wood flour, lignin, wood chips, and various cellulosic waste such as cotton fiber rejects. Treating wood pulp with alkali results in a colorless filler used in thermosetting resins such as phenolic. Also called pulp, cellulose pulp, alpha cellulose.

chain scission Breaking of the chainlike molecule of a polymer as a result of chemical, photochemical, etc. reaction such as thermal degradation or photolysis.

chamfer A beveled edge or corner; to bevel a sharp edge.

Chelation A chemical process in which a heterocyclic ring is formed that contains at least one metal cation or hydrogen in the ring.

chemical resistance Degradation of a material caused by chemical reaction.

chemical saturation Absence of double or triple bonds in a chain organic molecule such as that of most polymers, usually between carbon atoms. Saturation makes the molecule less reactive and polymers less susceptible to degradation and crosslinking.

chemical unsaturation Presence of double or triple bonds in a chain organic molecule such as that of some polymers, usually between carbon atoms. Unsaturation makes the molecule more reactive, especially in free-radical addition reactions such as addition polymerization, and polymers more susceptible to degradation, crosslinking and chemical modification.

chill roll cast film process A film extrusion process in which a plastics web is extruded from a slit die against the surface of a water-cooled, cored roll, the surface of which is highly polished.

chiral A molecule with a three-dimensional structure that cannot be superimposed on its mirror image. Because the mirror image forms do not cancel out molecular rotations in the presence of polarized light, chiral molecules are observed to rotate the plane of polarized light.

chloroprene rubber *See neoprene rubber.*

chopped glass fiber Chopped glass fibers have lengths from 1/8 to 1/2 in. and are made by chopping glass strands containing 8 120 filaments. The individual fibers are bonded together within strands so that they can remain in bundles after chopping. Used widely in bulk molding compounds; and compression, transfer, and injection molding. Also called short glass fiber, medium glass fiber, chopped strand.

chopped strand *See chopped glass fiber.*

chromic acid etching In adhesive bonding, a surface preparation technique in which chromic acid is used to introduce oxygenated reactive molecular groups, such as hydroxyl, carbonyl, carboxylic, and hydrogen sulfite, to the part surface and to form root-like cavities as sites for mechanical interlocking. Commonly used for polyolefins, ABS, polystyrene, polyphenyleneoxide, and acetals.

clarity Clarity is a measure of the amount of opaque suspended solids in a liquid, determined by visual or optical methods.

coated molybdate orange pigment Solid solutions of lead chromate, lead molybdate and lead sulfate and used as dark orange to light red inorganic pigments for plastics. Coated with silica, these pigments exhibit high hiding power, brightness, lightfastness, thermal stability and resistance to bleeding.

cobalt-60 One of the unstable isotopes of Co used widely as a source of gamma radiation.

cocatalyst *See accelerator.*

coefficient of linear thermal expansion The change in unit of length or volume that occurs due to a unit change in temperature. The expansion and contraction of a material with changes in temperature depend on its coefficient of linear thermal expansion, and movement of a part that is attached to another part with a lower CLTE value may be restricted.

coextruded film A film made by coextrusion of 2 or more different or similar plastics through a single die with two or more orifices arranged so that the extrudates merge and weld together into a laminar film before cooling. Each ply of coextruded film imparts a desired property, such as impermeability or resistance to some environment and heat-sealability, usually unattainable with a single material.

cohesive failure Failure of an adhesive bond that occurs within the adhesive, leaving adhesive present on both adherends. Optimum failure is 100% cohesive failure, when both shear areas are completely covered. See also adhesive failure.

colloidal carbon *See carbon black.*

compressive strain The relative length deformation exhibited by a specimen subjected to a compressive force. See also strain, flexural strain, tensile strain.

conditioning Process of bringing the material or apparatus to a certain condition, e.g., moisture content or temperature, prior to further processing, treatment, etc. Also called conditioning cycle.

conditioning cycle *See conditioning.*

conduction In heat transfer, migration of energy due to a temperature gradient. Heat energy is transferred by the movement of molecules at hotter or colder temperatures, with different degrees of thermal motion, into colder or hotter regions, respectively. See also radiation convection.

contact adhesive An adhesive that will adhere to itself on contact. When applied to both adherends, it forms a bond after drying, without sustained pressure on the adherends. Composed of neoprene or, less commonly, nitrile elastomers. See also pressure sensitive adhesive.

continuous glass fiber Continuous glass fibers are strands of filaments (roving) made by melt drawing from various grades of glass. Can be twisted. Used in sheet molding compounds, sprayup lamination, pultrusion, and filament winding. Continuous glass fibers provide fast wetout, even tension, and abrasion resistance during processing. Also called long glass fiber, continuous strand roving, continuous roving, continuous glass roving.

continuous glass roving *See continuous glass fiber.*

continuous roving *See continuous glass fiber.*

continuous strand roving *See continuous glass fiber.*

convection The mass movement of particles arising from the movement of a streaming fluid due to difference in a physical property such as density, temperature, etc. Mass movement due to a temperature difference results in heat

transfer, as in the upward movement of a warm air current. See also radiation, conduction.

conventional aging Prolonged exposure of materials such as plastics to natural or artificial environmental conditions to produce degradation as in weatherability testing, without accelerating the process by using above normal temperature, irradiation, etc.

corona discharge treatment In adhesive bonding, a surface preparation technique in which a high electric potential is discharged by ionizing the surrounding gas, usually air. The gas reacts with the plastic, roughening the surface to provide sites for mechanical interlocking and introducing reactive sites on the surface. Functional groups such as carbonyls, hydroxyls, hydroperoxides, aldehydes, ethers, esters, carboxylic acids, and unsaturated bonds have been proposed as reactive sites. Commonly used for polyolefins, corona discharge increases wettability and surface reactivity. In processing plastics, treating the surface of an inert plastic such as polyolefin with corona discharge to increase its affinity to inks, adhesives or coatings. Plastic films are passed over a grounded metal cylinder with a pointed high-voltage electrode above it to produce the discharge. The discharge oxidizes the surface, making it more receptive to finishing. Also called corona treatment. See also plasma arc treatment.

corona treatment See *corona discharge treatment*.

Coulombic friction The opposing force that occurs when two dry surfaces are rubbed together, as in vibration and spin welding. Also called external friction. See also internal friction.

coupler In ultrasonic welding, a booster that does not affect the amplitude of the horn. Its gain ratio is 1:1.

covalent bond A bond formed by the sharing of two or more electrons between two atoms. Covalent bonds can be single (two electrons shared), double (four shared electrons), or triple (6 shared electrons).

cracking Appearance of external and/or internal cracks in the material as a result of stress that exceeds the strength of the material. The stress can be external and/or internal and can be caused by a variety of adverse conditions: structural defects, impact, aging, corrosion, etc. or a combination thereof. Also called resistance to cracking, grazing, cracking resistance. See also crazing.

cracking resistance See *cracking*.

crazing Appearance of thin cracks on the surface or minute frost-like internal cracks in materials such as plastic as a result of residual stress, impact, temperature changes, degradation, etc. See also cracking.

creep Non-recoverable deformation in a part subjected to a continuous load. Creep is dependent on temperature and the duration and amount of the load.

crosslinked PE See *crosslinked polyethylene*.

crosslinked polyethylene Polyethylene thermoplastic partially crosslinked by irradiation or by the use of chemical additives such as peroxides to improve tensile strength, dielectric properties and impact strength over a wider range of temperatures. Also called crosslinked PE.

crosslinking Reaction or formation of covalent bonds between chain-like polymer molecules or between polymer molecules and low-molecular compounds such as carbon black fillers. As a result of crosslinking polymers, such as thermosetting resins, may become hard and infusible. Crosslinking is induced by heat, UV or electron-beam radiation, oxidation, etc. Crosslinking can be achieved either between polymer molecules alone as in unsaturated polyesters or with the help of multifunctional crosslinking agents such as diamines that react with functional side groups of the polymers. Crosslinking can be catalyzed by the presence of transition metal complexes, thiols and other compounds.

crystalline melting point The temperature of melting of the crystalline phase of a crystalline polymer. It is higher than the temperature of melting of the surrounding amorphous phase.

crystalline plastic See *semicrystalline plastic*.

curing A process of hardening or solidification involving crosslinking, oxidizing, and/or polymerization (addition or condensation).

cyanoacrylate In adhesive bonding, a highly reactive class of adhesives that cures rapidly at room temperature with trace amounts of moisture as catalysts to form high strength bonds with plastics and metals.

cyclohexane (C₆H₁₂) A colorless liquid with a pungent odor. Molecular structure is an alicyclic hydrocarbon that can exist in two conformations, the "boat" and "chair", depending on bond angles between carbon atoms. Soluble in alcohol, acetone, benzene; insoluble in water. Boils at 807°C (1485°F); freezes at 6.3°C (43°F). Its autoignition temperature is 473°F (145°C). It is a dangerous fire risk; flammable limit in air is 1.3–8.4%. Its TLV is 300 ppm in air; it is moderately toxic by inhalation and skin contact. Derived from crude petroleum or by catalytic hydrogenation of benzene. Used in the production of nylon, in the extraction of essential oils; as a solvent for cellulose ethers, fats, oils, crude rubber, bitumens, resins, waxes; in organic synthesis; as a paint and varnish remover and in glass substitutes. Also called hexamethylene, hexanaphthene, hexalhydrobenzene.

cyclohexanone (C₆H₁₀O) Cyclohexanone is an oily, water-white to pale yellow liquid with a slight odor of peppermint and acetone. Soluble in organic solvents such as alcohols and ethers, slightly soluble in water. It has an autoignition temperature of 420°C (788°F). Its TLV is 25 ppm in air; it is toxic by inhalation and skin contact. Derived by passing cyclohexanol over copper with air at 138°C (280°F) or by oxidation of cyclohexanol with chromic acid or oxide. Used in the preparation of adipic acid, caprolactam, polyvinyl chloride and its copolymers, and methacrylate ester polymers, and for metal degreasing. Used in wood stains, paint and varnish removers, spot removers, polishes, natural and synthetic resins, lube oil, and other products. Also called pimelic ketone, keto-hexamethylene.

D

damping In part assembly, to mechanically limit the amplitude of vibration in the parts being assembled.

dart impact energy The mean energy of a free-falling dart that will cause 50% failures after 50 tests to a specimen directly stricken by the dart. The energy is calculated by multiplying dart mass, gravitational acceleration and drop height. Also called falling dart impact strength, dart impact strength.

dart impact strength *See dart impact energy.*

deflection temperature under load *See heat deflection temperature.*

degradation Loss or undesirable change in properties as a result of aging, chemical reactions, wear, use, exposure, etc. The properties include color, size, strength, etc. *See also degradation.*

denier A measure of the fineness of a fiber or yarn. One denier is equal to the weight in grams of 9000 meters of yarn or fiber; the lower the denier, the finer the yarn.

density The mass of any substance (gas, liquid or solid) per unit volume at specified temperature and pressure. The density is called absolute when measured under standard conditions, e.g., 760 mmHg pressure and 0°C temperature. Note: For plastics- the weight in air per volume of impermeable portion of the material measured at 23°C according to ASTM D792. Also called mass density, absolute gravity, absolute density.

dicyandiamide (NH₂C(NH)(NHCN)) White crystals that are stable when dry. Soluble in liquid ammonia; partly soluble in hot water. Melts at 207–209°C (405–408°F). Not flammable. Derived from polymerization of cyanamide in the presence of bases. Used as a catalyst for epoxy resins, a stabilizer in detergents, a modifier in starch products, a thinner in oil-well drilling muds; in organic reactions, fertilizers, pharmaceuticals, dyestuffs, case-hardening preparations, soldering compounds; and many other uses. Also called cyanoguanidine.

dielectric dissipation factor The ratio of the power dissipated in a dielectric to the product of the effective voltage and the current; or the cotangent of the dielectric phase angle; or the tangent of dielectric loss angle. Note: For plastics measured according to ASTM D150. Also called tan delta, permittivity loss factor, dissipation factor, dielectric loss tangent.

dielectric loss tangent *See dielectric dissipation factor.*

differential scanning calorimetry DSC is a technique in which the energy absorbed or produced is measured by monitoring the difference in energy input into the substance and a reference material as a function of temperature. Absorption of energy produces an endotherm; production of energy results in an exotherm. May be applied to processes involving an energy change, such as melting, crystallization, resin curing, and loss of solvents, or to processes involving a change in heat capacity, such as the glass transition.

dimethyl ketone *See acetone.*

direct contact hot tool welding A form of heated tool welding in which the thermoplastic parts are pressed directly against the hot tool or plate. Part surfaces are heated until the melting or glass transition is reached. The hot tool is then removed, and the parts are pressed together until cooled. The hot tool can be coated with polytetrafluoroethylene to reduce melt sticking. *See also heated tool welding, hot tool welding.*

dissipation factor *See dielectric dissipation factor.*

dissolving capacity *See solubility.*

driving torque In mechanical fastening, the force necessary to drive a self-tapping screw into a pilot hole. Lower values are optimal.

drop dart impact strength *See falling weight impact energy.*

drop weight impact strength *See falling weight impact energy.*

DSC *See differential scanning calorimetry*

durability *See stability.*

durometer hardness Indentation hardness of a material as determined by either the depth of an indentation made with an indenter under specified load or the indenter load required to produce a specified indentation depth. The tool used to measure indentation hardness of polymeric materials is called a durometer, e.g., Shore-type durometer.

dynamic fatigue Fatigue occurring under a load that varies periodically, usually sinusoidally.

E

elasticity Property whereby a solid material changes its shape and size under action of opposing forces, but recovers its original configuration when the forces are removed.

elasticity constant *See modulus of elasticity.*

electrofusion welding A technique used for joining thermoplastic pipes or liners, in which electricity is applied to a heating element surrounded by a thermoplastic material. The heat produced causes the thermoplastic material and the thermoplastic on the surface of the pipes to melt and flow together, forming a weld. Commonly used for joining polyethylene pipes.

electromagnetic radiation Waves of electric charges propagated through space by oscillating electromagnetic fields and associated energy.

electromagnetic welding *See induction welding.*

electron beam *See electron beam radiation.*

electron beam radiation Ionizing radiation propagated by electrons that move forward in a narrow stream with approximately equal velocity. Also called electron beam.

Elmendorf tear strength The resistance of flexible plastic film or sheeting to tear propagation. It is measured, according to ASTM D1922, as the average force, in grams, required to propagate tearing from a precut slit through a specified length, using an Elmendorf-type pendulum tester and 2 specimens, a rectangular type and one with a constant radius testing length.

elongation The increase in gauge length of a specimen in tension, measured at or after the fracture, depending on the viscoelastic properties of the material. Note: Elongation is usually expressed as a percentage of the original gage length. Also called ultimate elongation, tensile elongation, breaking elongation.

elongation at break The increase in distance between two gauge marks, resulting from stressing the specimen in tension, at the exact point of break. Measurement taken at the exact point of break according to ASTM D638.

energy director A triangular shaped bead of plastic that is molded into one of the parts to be joined. Used in ultrasonic welding, it concentrates ultrasonic energy at the point, resulting in rapid heat buildup and melting.

energy quencher A low-molecular-weight organic compound such as polycyclic aromatic compound that retards ionizing radiation-induced polymer degradation by scavenging or trapping part of excited-state energy of the polymer without undergoing significant chemical change due to the highly efficient decay of its own excited states.

environmental stress cracking Cracking or crazing that occurs in a thermoplastic material subjected to stress or strain in the presence of particular chemicals or weather conditions or as a result of aging. Also called ESC.

EP See *epoxy resin*.

EPDM See *EPDM rubber*.

EPDM rubber Ethylene propylene-diene terpolymer (EPDM) rubbers are produced from ethylene, propylene, and smaller amounts of a nonconjugated diene such as hexadiene. They are vulcanized using sulfur. Typical properties include excellent resistance to oxygen, ozone, light, high and low temperatures, acids, alkalies, and oils. They may be used in other elastomers as impact modifiers and also to improve heat and ozone resistance. Typical uses include weather stripping, auto parts, cable insulation, conveyor belts, garden and industrial hoses, and appliance tubing. EPDM rubbers have been proposed as potential substitutes for natural rubber in tires. Also called ethylene propylene diene monomer rubber, EPDM.

EPM See *ethylene propene rubber*.

epoxides Organic compounds containing three-membered cyclic group(s) in which two carbon atoms are linked with an oxygen atom as in an ether. This group is called an epoxy group and is quite reactive, allowing the use of epoxides as intermediates in preparation of certain fluorocarbons and cellulose derivatives and as monomers in preparation of epoxy resins.

epoxy See *epoxy resin*.

epoxy resin Epoxy resins are a family of thermoset polyethers containing crosslinkable glycidyl groups. The largest group of epoxy resins is prepared by polymerization of bisphenol A and epichlorohydrin. These resins have a wide viscosity range, depending on their molecular weight, and are cured at room or elevated temperatures with catalyzed polyamines and/or anhydrides. Aliphatic and cycloaliphatic epoxy resins are produced by peroxidation of olefins with peracetic acid or epoxidation of polyols with epichlorohydrin. Novolak epoxy resins are prepared by reacting novo-

lak phenolic resins with epichlorohydrin. Vinyl ester or acrylic epoxy resins are prepared by treating epoxy resins with unsaturated carboxylic acids such as acrylic acid. There are other specialty type epoxy resins such as halogenated epoxy and phenoxy resins. Bisphenol A epoxy resins exhibit excellent adhesion and very low shrinkage during curing. Additionally, cured novolak and cycloaliphatic resins have good UV stability and dielectric properties, while cured vinyl ester resins show high strength and chemical resistance and brominated epoxy resins show fire retardant properties. Some epoxy resins have poor oxidative stability. Processed by injection, compression, transfer, and structural foam molding, casting, coating, and lamination. Widely used as protective coatings, adhesives, potting compounds, and binders in laminates, flooring, civil engineering, electrical and electronic products. Also called epoxy, EP, bisphenol A epoxy resin.

epoxyethane See *ethylene oxide*.

EPP bead See *polypropylene*.

EPR See *ethylene propene rubber*.

ESC See *environmental stress cracking*.

etching In adhesive and solvent bonding, a process used to prepare plastic surfaces for bonding. Exposure of the plastic parts to a reactive chemical, such as chromic acid, or to an electrical discharge results in oxidation of the surface and an increase in surface roughness by removal of surface material.

ethane An alkane (saturated aliphatic hydrocarbon) with 2 carbon atoms, CH_3CH_3 . A colorless, odorless, flammable gas. Relatively inactive chemically. Obtained from natural gas. Used in petrochemical synthesis and as fuel.

ethanol See *ethyl alcohol*.

ethene See *ethylene*.

ethyl acetate An ethyl ester of acetic acid, $\text{CH}_3\text{CO}_2\text{CH}_2\text{CH}_3$. A colorless, fragrant, flammable liquid. Autoignition temperature 426°C . Toxic by inhalation and skin absorption. Derived by catalytic esterification of acetic acid with ethanol. Used as solvent in coatings and plastics, organic synthesis, artificial flavors, pharmaceuticals.

ethyl alcohol An aliphatic alcohol, $\text{CH}_3\text{CH}_2\text{OH}$. A colorless, volatile, flammable liquid. Autoignition point is 422°C . Toxic by ingestion. Derived by catalytic hydration of ethylene, fermentation of biomass such as grain, or enzymatic hydrolysis of cellulose. Used as automotive fuel additive, in alcoholic beverages, as solvent for resins and oils, in organic synthesis, cleaning compositions, cosmetics, antifreeze, and antiseptic. Also called ethanol.

ethylene An alkene (unsaturated aliphatic hydrocarbon) with two carbon atoms, $\text{CH}_2=\text{CH}_2$. A colorless, highly flammable gas with sweet odor. Autoignition point 543°C . Derived by thermal cracking of hydrocarbon gases or from gas synthesis. Used as monomer in polymer synthesis, refrigerant, and anesthetic. Also called ethene.

ethylene methyl acrylate copolymer Thermoplastic resins prepared by high-pressure polymerization of ethylene and <40% methyl acrylate. The resins are characterized by good dielectric properties, toughness, thermal stability, and resistance to environmental stress cracking.

They also have good processibility in LDPE equipment. They exhibit high compatibility with other polyolefins and permit high levels of filling. Optical properties deteriorate with increasing content of acrylate. Processed by blown film extrusion, extrusion, blow molding, and injection molding. Uses include coatings, heat-sealable film, disposable gloves, and antiseptic packaging. Meet FDA requirements for food packaging. Also called methyl acrylate ethylene polymer, EMAC.

ethylene polymers Ethylene polymers include ethylene homopolymers and copolymers with other unsaturated monomers, most importantly olefins such as propylene and polar substances such as vinyl acetate. The properties and uses of ethylene polymers depend on the molecular structure and weight.

ethylene propene rubber Ethylene propylene rubbers (EPR) are elastomers prepared by stereospecific polymerization of ethylene with propylene. The properties of EPR are similar to those of natural rubber. Used as impact modifiers for plastics and in tires. Also called ethylene propylene rubber, EPR, EPM.

ethylene propylene diene monomer rubber *See EPDM rubber.*

ethylene propylene rubber *See ethylene propene rubber.*

ethylene propylene terpolymer A polymer consisting of ethylene, propylene and one component not identified.

ethylene tetrafluoroethylene copolymer Thermoplastic comprised of an alternating copolymer of ethylene and tetrafluoroethylene. Has high impact resistance and good abrasion resistance, chemical resistance, weatherability, and electrical properties, approaching those of fully fluorinated polymers. Retains mechanical properties from cryogenic temperatures to 356°F. Can be molded, extruded, and powder coated. Used in tubing, cable and wire products, valves, pump parts, wraps, and tower packing in aerospace and chemical equipment applications. Also called ETFE.

ethylene vinyl alcohol copolymer EVOH resins are thermoplastics prepared by hydrolysis of ethylene-vinyl acetate copolymers. The resins have excellent gas and vapor barrier properties, high mechanical strength, gloss, elasticity, weatherability, and resistance to solvents and oils. The clarity, surface hardness, and abrasion resistance of EVOH resins are high. They absorb moisture which affects their performance as vapor barriers. The processibility of the resins improves and the absorption of moisture decreases with increasing content of ethylene. Processed by (co)extrusion, coating, blow molding, thermofforming, and film techniques. Used mainly as packaging films and container liners for food and nonfood items. Also called EVOH. Also called EAA

ethylene-acrylic acid copolymer A flexible thermoplastic with water and chemical resistance and barrier properties similar to those of low-density polyethylene and enhanced adhesion, optics, toughness, and hot tack properties, compared to the latter. Contains 3-20% acrylic acid, with density and adhesion to polar substrates increasing with increasing acrylic acid content. FDA-approved for direct contact with food. Processed by ex-

trusion, blow and film methods and extrusion molding, and extrusion coating. Used in rubberlike small parts like pipe caps, hoses, gaskets, gloves, hospital sheeting, diaper liners, and packaging film.

ETO *See ethylene oxide.*

EVOH *See ethylene vinyl alcohol copolymer.*

expandable polyethylene bead *See polyethylene.*

expandable polypropylene bead *See polypropylene.*

extenders Relatively inexpensive resin, plasticizer or filler such as carbonate used to reduce cost and/or to improve processing of plastics, rubbers or nonmetallic coatings.

extrusion Process for converting of an ingot or billet into lengths of uniform cross section by forcing material to flow plastically through a die orifice; a product form produced by this process. There are many variations of this process used widely in working metals and processing plastics.

extrusion blow molding *See blow molding, extrusion.*

extrusion welding A joining process in which molten thermoplastic material is extruded into a groove in a preheated seam. The extruded thermoplastic material fills the groove and cools, welding the two parts together. Commonly used for joining membranes and pipes with thermoplastic liners.

F

falling dart impact strength *See dart impact energy.*

falling weight impact energy The mean energy of a free-falling dart or weight (tup) that will cause 50% failures after 50 tests to a directly or indirectly stricken specimen. The energy is calculated by multiplying dart mass, gravitational acceleration and drop height. Also called falling weight impact strength, drop weight impact strength, drop dart impact strength.

falling weight impact strength *See falling weight impact energy.*

far field Refers to the distance that ultrasonic energy is transmitted from the horn to the joint interface in ultrasonic welding. Far field welding occurs when the joint is more than 0.25 in. (6.4 mm) from the point at which the horn contacts the part. See also near field.

fatigue Process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations, according to ASTM E1150. See also flexural fatigue, tensile fatigue.

fatigue life Number of loading-unloading cycles of a specified type that material specimen can endure before failing in a fatigue test.

fatigue strength The limiting value of the median fatigue strength as the number of loading cycles sustained before failure becomes very large. Fatigue strength, here, is the maximum stress that can be sustained without failure at this number of loading cycles.

feedstock recycling A plastics recycling method in which waste materials are broken down into their constituent monomers or into liquid or gaseous hydrocarbons. Also called raw material recycling. See also mechanical recycling, thermal recycling.

ferromagnetic material Materials such as stainless steel and iron, in which the magnetic moments or dipoles of atoms exhibit a high degree of alignment parallel to each other in the presence of a magnetic field. This alignment is in opposition to the usual tendency of atoms to orient in random directions due to thermal motion. Used in induction welding.

fiber staple Short-length fibers. Most natural fibers, such as cotton, jute, and wool, are staple fibers, with lengths varying from two to several hundred centimeters. Man-made polymer fibers are produced as continuous fibers; staple fibers are formed by chopping and crimping continuous fibers, then pressing them into a bale.

fiber tow An untwisted bundle of continuous filaments.

filament The smallest unit of a fibrous material, formed during drawing or spinning.

filler A relatively inert substance added to plastics to reduce their cost and/or improve physical properties such as impact strength. In contrast to reinforcement, filler particles are usually nonfibrous, small, and do not improve the tensile strength. The fillers are added to the plastics at fairly high percentages (>5 vol.%). The most important fillers are mineral and glass fillers. Based on their use, the fillers are also classified as extenders and reinforcing fillers. See also mineral filler, organic filler.

film A product, e.g., plastic, that is extremely thin compared to its width and length. There are supported and unsupported films such as coatings and packagings, resp.

fireproofing agent *See flame retardant.*

fixture In part assembly, a device used to align and support the parts during assembly. Also called a nest. Also called nest.

flame retardant A substance that reduces the flammability of materials such as plastics or textiles in which it is incorporated. There are inorganic flame retardants such as antimony trioxide (Sb_2O_3) and organic flame retardants such as brominated polyols. The mechanisms of flame retardation vary depending on the nature of material and flame retardant. For example, some flame retardants yield a substantial volume of coke on burning, which prevents oxygen from reaching inside the material and blocks further combustion. Also called fireproofing agent.

flame treatment In adhesive bonding, a surface preparation technique in which the plastic is briefly exposed to a flame. Flame treatment oxidizes the surface through a free radical mechanism, introducing hydroxyl, carbonyl, carboxyl, and amide functional groups to a depth of ~4–6 nm, and produces chain scissions and some crosslinking. Commonly used for polyolefins, polyacetals, and polyethylene terephthalate, flame treatment increases wettability and interfacial diffusivity.

flash In welding thermoplastics, molten plastic that seeps out of the joint area during the welding process. In molding, surplus plastic attached to the molding along the

parting line. Flash must usually be removed before parts are considered to be finished.

flexural fatigue Progressive localized permanent structural change occurring in a material subjected to cyclic flexural stress that may culminate in cracks or complete fracture after a sufficient number of cycles.

flexural fatigue strength Maximum stress that can be sustained for a specified number of bending cycles without failure.

flexural modulus of elasticity The ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.

flexural properties Properties describing the reaction of physical systems to flexural stress and strain.

flexural strain The tensile elongation on the surface of a cross section opposite to that experiencing a locally impinging force in bending at any time of the test. See also strain, compressive strain, tensile strain.

flexural strength The maximum stress in the extreme fiber of a specimen loaded to failure in bending. Note: Flexural strength is calculated as a function of load, support span and specimen geometry. Also called modulus of rupture, bending strength.

flexural stress The maximum fiber stress in a specimen at a given strain in a bending test. The maximum fiber stress is a function of load, support span, and specimen width and depth. It depends on the method of load application relative to the supports and on the specimen geometry. It has to be calculated. Note: Flexural stress is calculated as a function of load at a given strain or at failure, support span and specimen geometry.

fluoroelastomer Fluoroelastomers are a class of synthetic elastomers designed for demanding service applications. They possess excellent resistance to corrosive fluids and other chemicals, as well as to high temperatures. Typical applications include automotive fuel line hoses, o-rings, shaft seals, engine oil and coolant seals, and carburetor fuel pumps. Fluoroelastomers may be used as additives for polyolefins to improve extrusion properties. Also called fluoro rubber.

fluorohydrocarbon resin *See fluoropolymer.*

fluoroplastic *See fluoropolymer.*

fluoropolymer Thermoplastics comprised of mostly polyolefins that have all or some of the hydrogen atoms replaced by fluorine. Characterized by excellent chemical resistance, antifriction properties, thermal stability, antiadhesive properties, low flammability, and weatherability. The disadvantages include low creep resistance and strength and insufficient ease in processing. The properties of fluoropolymers depend on the content of fluorine. The processing is achieved by extrusion and molding. The uses are chemical apparatus, bearings, films, coatings, and containers. Also called polyfluorohydrocarbon, polyfluorocarbon, fluoroplastic, fluorohydrocarbon resin, fluorocarbon resin.

foam *See polymeric foam.*

foaming agent *See blowing agent.*

formula weight *See molecular weight.*

fountain flow The ballooning or stretching of the flow of melt into a mold cavity from an injection molding machine. The melt front becomes oriented and stretched along the inside wall of the mold; the remaining melt fills in behind the fountain flow.

Fourier transform infrared spectroscopy FTIR is a spectroscopic technique in which a sample is irradiated with electromagnetic energy from the infrared region of the electromagnetic spectrum (wavelength ~0.7 to 500 mm). The sample is irradiated with all infrared wavelengths simultaneously, and mathematical manipulation of the Fourier transform is used to produce the absorption spectrum or "fingerprint" of the material. Molecular absorptions in the infrared region are due to rotational and vibrational motion in molecular bonds, such as stretching and bending. FTIR is commonly used for the identification of plastics, additives, and coatings.

fractional melt index resin Thermoplastics having a low melt index of <1. These resins have higher molecular weights and are harder to extrude because of lower rate and greater force requirements compared to the lower molecular weight resins. They are mainly used for heavy duty applications such as pipe.

free radical An atom or group of atoms with an odd or unpaired electron. Free radicals are highly reactive and participate in free radical chain reactions such as combustion and polymer oxidation reactions.

free surface energy *See surface tension.*

frequency The number of cycles completed by a periodic quantity in a unit time.

friction welding A welding method for thermoplastics in which friction provides the heat necessary to melt the parts at the joint interface. Friction welding methods include spin welding and vibration welding.

G

gain In ultrasonic welding, the ratio of output amplitude to input amplitude of a horn or booster. *See also* horn, booster.

gamma radiation Ionizing radiation propagated by high-energy protons, e.g., emitted by a nucleus in transition between two energy levels.

general purpose polystyrene General purpose polystyrene is an amorphous thermoplastic prepared by homopolymerization of styrene. It has good tensile and flexural strengths, high light transmission and adequate resistance to water, detergents and inorganic chemicals. It is attacked by hydrocarbons and has a relatively low impact resistance. Processed by injection molding and foam extrusion. Used to manufacture containers, health care items such as pipettes, kitchen and bathroom housewares, stereo and camera parts and foam sheets for food packaging. Also called crystal polystyrene.

generator An electronic device that converts standard 120/240 volt, 50/60 Hz line voltage into high-frequency electrical energy.

glass fiber Glass fibers are a large family of short (staple, chopped, milled) or continuous fiber reinforcement, used widely in both thermosets and thermoplastics for increased strength, dimensional stability, thermal stability, corrosion resistance, and dielectric properties. The fibers are made by the melt drawing of various grades (electric, chemical, high tensile strength) of glass and are comprised of strands of filaments (roving) that can be further processed by size reduction, twisting, or weaving into fabrics or mats. Used in molding compounds, sprayup processes, die molding, layup, and other lamination processes. Glass fibers are often surface modified, e.g., with coupling agents, to improve bonding with polymer matrix or to impart special properties such as electrical conductivity (by coating with nickel). Also called glass roving.

glass filler Glass fillers are a widely used family of fillers in the form of beads, hollow spheres, flakes, or milled particles. They increase dimensional stability, chemical resistance, moisture resistance, and thermal stability of plastics.

glass roving *See glass fiber.*

graphite fiber *See carbon fiber.*

graphite filler A crystalline form of carbon in powder form. Graphite occurs naturally and also is produced by heating petroleum coke, carbon black, and organic materials. Used as a lubricating filler for nylons and fluoropolymers. Also called powdered graphite, plumbago, graphite powder, carbon graphite, black lead.

graphite powder *See graphite filler.*

grazing *See cracking.*

H

halide An element in Group VII of the Periodic Table of the elements, which consists of fluorine, chlorine, bromine, iodine, and astatine.

HAL *See hindered amine light stabilizer.*

hard clays Sedimentary rocks composed mainly of fine clay mineral material without natural plasticity, or any compacted or indurated clay.

hardness The hardness of a solid substance is the resistance to indentation, scratching, abrasion, or cutting.

HAZ *See heat affected zone.*

haze The percentage of transmitted light which, in passing through a plastic specimen, deviates from the incident beam via forward scattering more than 2.5 degrees on average (ASTM D883).

HDPE *See high density polyethylene.*

HDT *See heat deflection temperature.*

heat affected zone In welding, the region of the part that is affected by heat used to melt the joining surface. Microstructure of the heat affected zone is an important determinant of the mechanical strength of the weld. Also called HAZ.

heat deflection temperature The temperature at which a material specimen (standard bar) is deflected by a certain degree under specified load. Also called tensile heat dis-

tortion temperature, heat distortion temperature, HDT, deflection temperature under load.

heat distortion temperature See *heat deflection temperature*.

heat seal temperature Temperature of a thermoplastic film or sheet required to join two or more films or sheets in contact by fusion.

heat sealing A method of joining plastic films by the simultaneous application of heat and pressure to the areas in contact. Heat can be applied using hot plate welding, dielectric heating, or radio-frequency welding.

heat stability See *thermal stability*.

heated tool welding A method for joining thermoplastic parts in which a hot plate or hot tool is used to provide heat to melt the joining surfaces. The tool is then removed, and the parts are pressed together. While in the molten state, molecular diffusion across the joint interface occurs, and a homogeneous, permanent bond is formed after the parts are allowed to cool. A hot plate is used for flat surfaces and a hot tool in the shape of the joint for irregularly shaped surfaces. Also called fusion bonding, heat sealing, hot shoe welding, butt fusion., hot plate welding.

hermetic seal A seal or weld that is impervious to liquids and air and other gases; airtight.

hiding power The capacity of a coating material such as paint and, by extension, of the pigment in it to render invisible or cover up a surface on which it is applied as a film. For paints, hiding power is often expressed in gallons per square foot.

high density polyethylene HDPE is a linear polyethylene with density 0.94-0.97 g/cm³, molecular weight 50,000-250,000, and high crystallinity. Produced by co- or homopolymerization in a slurry or gas phase at relatively low pressure and temperature. High-density polyethylene has excellent low temperature toughness, chemical resistance, good dielectric properties, and relatively high softening temperatures, but poor weatherability. The properties improve with decreasing polydispersity. Processed by extrusion, blow molding, injection molding, rotational molding, and powder coating. Used as films and coatings and in housewares, containers, food packaging, liners, cable insulation, profiles, pipes, bottles, and toys. Also called HDPE.

high molecular weight low density polyethylene The thermoplastic polyolefin with improved environmental stress crack resistance, impact strength and abrasion resistance but reduced flow processibility and tensile strength. Also called HMWLDPE.

hindered amine light stabilizer Amines, such as piperidine derivatives, with bulky, sterically hindered molecular structure. These light stabilizers photooxidize readily to nitroxyl radicals that neutralize, via recombination, alkyl radicals formed during photodegradation of polymers such as polyolefins and therefore retard this process.

HMWLDPE See *high molecular weight low density polyethylene*.

hold time In welding, the length of time allotted for the melted plastic to solidify. In process engineering, the residence time of an individual ingredient in reaction vessel or other processing apparatus. Also called holding time.

holding load In mechanical fastening, the load required in tensile tests to pull an insert or screw out of the surrounding plastic.

holding time See *hold time*.

homolytic cleavage Symmetrical cleavage of a two-electron covalent bond. Each atom receives one electron, producing two free radicals. See also free radicals

homopolymer A polymer that contains only a single type of monomer (i.e. propylene). See also block copolymer, random copolymer, random block copolymer.

hoop stress The tensile or circumferential stress in the wall of a material of cylindrical form subjected to internal or external pressure.

horn An acoustical tool designed to transfer mechanical vibrations from the transducer-booster assembly directly to the parts to be assembled. See also coupler.

hot air welding See *hot gas welding*.

hot gas welding A method for joining thermoplastic materials in which the parts are softened by hot gas, usually air, from a welding torch and joined together at the softened points. A filler rod composed of the same material as the part is generally used to fill and consolidate the gap between the parts. Hot gas welding is used for joining and repair of thermoplastic parts and for lap welding of thin sheets. Also called hot air welding.

hot knife sealing A joining process in which a heated tool in the form of a knife blade is passed between the parts being joined, so that heat is applied to the seal side of the part. The blade is then removed, and surfaces are pressed together for a few seconds until the bond solidifies.

hot melt adhesive An adhesive that is applied in a molten state which forms a bond after cooling to a solid state. Acquires adhesive strength through cooling, unlike adhesives that achieve strength through solvent evaporation or chemical cure.

hot plate welding See *heated tool welding*.

hot tack strength The force required to separate a molten seal in heat-sealable thermoplastic films. It determines the rate at which the film can be sealed.

hydrocarbon A chemical compound that contains only hydrogen and carbon atoms.

hydrophilic surface Surface of a hydrophilic substance that has a strong ability to bind, adsorb or absorb water; a surface that is readily wettable with water. Hydrophilic substances include carbohydrates such as starch.

hydroxy group See *hydroxyl group*.

hydroxyl group A combination of one atom of hydrogen and one atom of oxygen, -OH, attached by a single covalent bond to another atom, such as carbon, in a molecule of an organic or inorganic substance. It is a characteristic group of alcohols and hydroxides. Hydroxyl groups on the surface of a material usually make it hydrophilic. Hydroxyl groups are quite reactive, e.g., they readily undergo etherification or esterification. Also called hydroxy group.

impact copolymer *See block copolymer.*

impact strength The energy required to break a specimen, equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact with the specimen and the energy remaining after complete fracture of the specimen. Also called impact energy.

induction welding A technique used for joining plastics and other materials. High frequency, electromagnetic energy is used to excite molecules of a ferromagnetic material placed at the joint interface. The heat generated melts the surrounding thermoplastic matrix, fusing the two parts together. Also called electromagnetic welding. Also called magnetic induction welding, electromagnetic welding.

infrared welding A welding technique in which infrared radiation is used to heat the surfaces of thermoplastic parts to the melting temperature. Flow of molten material across the joint interface allows molecular diffusion and weld formation after cooling. Infrared radiation pertains to the region of the electromagnetic spectrum between visible light and radar. Wavelengths of from 1 to 15 mm (0.000039 to 0.00059 in.) are used in infrared welding.

injection blow molding *See blow molding, injection.*

injection molding A molding procedure in which a heat-softened plastic material is forced from a cylinder into a cavity which gives the article the desired shape. It is used for all thermoplastics and some thermosets.

injection molding pressure The pressure of the melt immediately before entering the mold.

initial tear resistance The force required to initiate tearing of a flexible plastic film or thin sheeting at very low rates of loading, measured as maximum stress usually found at the onset of tearing.

insert In mechanical fastening, an integral part of a plastic molding consisting of a metal, plastic, or other material that can be molded into the plastic or pressed into position after molding.

integral hinge *See living hinge.*

interference fit A mechanical fastening method used to join two parts, such as a hub and a shaft, in which the external diameter of the shaft is larger than the internal diameter of the hub. This interference produces high stress in the material and must be determined carefully to avoid exceeding the allowable stress for the material. Stress relaxation can occur in interference fits, causing the joint to loosen over time. Also called press fit.

internal friction Conversion of mechanical strain energy to heat in a material exposed to a fluctuating stress. See also Coulombic friction.

ion An electrically charged atom or group of atoms.

ionizing radiation dose *See radiation dose.*

ionomer Ionomers are thermoplastics containing pendant ionized acid groups which create ionic crosslinks between chains. Usually, only <10% repeating units of ionomers contain ionized groups, whereas polyelectrolytes contain substantially more. A typical commercial representative

of this group is ethylene methacrylic acid copolymer sodium salt. The ionomers offer high flex and impact toughness in the temperature range from -160 to +180°F. They have excellent resistance to puncture and to organic solvents, mild acids and bases, and edible oils; high adhesion to paper and other substrates; and good dielectric properties. Many ionomers are FDA approved for food packaging. Some disadvantages of ionomers are poor weatherability, flammability, and high thermal expansion. Processed by injection, blow, and rotational molding; blown and cast film extrusion; and extrusion coating. Used in packaging, shoe soles, auto bumper guards, laminated bags, sporting goods, and foam sheets.

isotactic A polymeric molecular structure in which atoms are regularly spaced in the same stereochemical configuration along the polymer chain. Isotactic plastics form crystallized morphological structures upon cooling. See also atactic, syndiotactic.

isotacticity index Stereoregularity of a polymer as determined by the percent polymer insoluble in boiling n-heptane. Isotacticity index is usually determined for commercial isotactic polypropylene and is valid only for crystallized polymer.

Izod *See Izod impact energy.*

Izod impact energy The energy required to break a v-notched specimen equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact with the specimen and the energy remaining after complete fracture of the specimen. For metals, it is measured according to ASTM E23. Also called notched Izod strength, notched Izod impact strength, Izod v notch impact strength, Izod strength, Izod impact strength, Izod, IVN.

Izod impact strength *See Izod impact energy.*

Izod strength *See Izod impact energy.*

Izod v notch impact strength *See Izod impact energy.*

J

J *See joule.*

jig A device used to hold parts in place and guide the tool during assembly or machining operations.

joint design Molding the shape of mating thermoplastic parts to achieve the intended assembly results.

joint efficiency A numerical value expressed as the ratio of the strength of the joint to the strength of the bulk material.

joule A unit of energy in SI system that is equal to the work done when the point of application of a force of one newton (N) is displaced through distance of one meter (m) in the direction of the force. The dimension of joule is N m. Also called J.

K

kinetic coefficient of friction The ratio of tangential force, which is required to sustain motion without acceleration of one surface with respect to another, to the normal force, which presses the two surfaces together.

L

lamella In plastics, the basic morphological unit of a crystalline polymer. Shaped like a thin plate or ribbon. Dimensions are usually approximately 10 nm (0.4 min.) thick, 1mm (40 min.) long, 0.1 mm (4 min.) wide (for ribbon-like shapes).

lap joint A joint in which one adherend is placed partly over the other adherend; overlapped areas are bonded together.

lap shear test *See ASTM D1002.*

laser A device used to produce an intense light beam with a narrow band width. Laser is an acronym for light amplification by stimulated emission of radiation.

laser welding A joining method for thermoplastics in which a high intensity laser beam is used to generate heat at the part surfaces, causing the materials to melt and coalesce.

LDPE *See low density polyethylene.*

Lewis base A substance that donates a pair of electrons in a chemical reaction to form a bond with another substance.

linear low density polyethylene LLDPE are linear carbon-chain copolymers of ethylene with higher alpha-olefins such as 1 butene and 1 hexene, having density 0.91-0.94 g/cm³. They are prepared by solution or gas-phase copolymerization. LLDPE have better tensile, tear, and impact strength and crack resistance properties, but poorer haze and gloss than those of low-density polyethylene. LLDPE are processed by extrusion, which requires increased pressure and higher melt temperatures than low-density polyethylene, and molding. Used as films and sheets and in pipes, electrical insulation, liners, bags, and food wraps. Also called LLDPE.

linear polyethylenes Linear polyethylenes are polyolefins with linear carbon chains. They are prepared by copolymerization of ethylene with small amounts of higher alpha-olefins such as 1-butene. Linear polyethylenes are stiff, tough and have good resistance to environmental cracking and low temperatures. Processed by extrusion and molding. Used to manufacture film, bags, containers, liners, profiles and pipe.

liquid crystal polymer Polymers exhibiting a crystalline phase in liquid, e.g., melt, state due to the presence of highly ordered molecular fragments. Also called liquid crystalline thermoplastic, liquid crystalline polymer.

liquid crystalline polymer *See liquid crystal polymer.*

liquid crystalline thermoplastic *See liquid crystal polymer.*

liquid injection molding system *See reaction injection molding system.*

living hinge A hinge molded into the part that provides bending action due to molecular orientation that runs transverse to the hinge axis. *See also orientation.*

LLDPE *See linear low density polyethylene.*

long glass fiber *See continuous glass fiber.*

low density polyethylene LDPE is a branched carbon-chain polyethylene thermoplastic prepared by homopolymerization of ethylene under high pressure. Its den-

sity is 0.91-0.94 g/cm³. It has high toughness, impact strength, flexibility, film transparency, chemical resistance, good dielectric properties, and low water permeability and brittleness temperature. It is susceptible to environmental stress cracking, weathering, burns, and has poor thermal stability. Processed by extrusion coating, injection and blow molding, and film techniques; cross-linkable. Used in packaging and shrink films, bags, laminates, toys, bottle caps, cable insulation, and coatings. Also called LDPE.

M

magnetic induction welding *See induction welding.*

marking In part assembly, the scuffing or marring of a plastic part, which detracts from its cosmetic appearance.

mass density *See density.*

maximum diametral interference In interference fit design, the maximum allowable interference for a particular hub and shaft, per unit measurement of shaft diameter. The maximum diametral interference depends on the types of materials used in the hub and shaft and on the ratio of shaft diameter to hub outside diameter. It is determined to ensure that hoop stress in the interference fit does not exceed the allowable stress of materials used in the design.

mechanical fastening A method of joining plastics and/or metals using fasteners such as machine screws, self-tapping screws, inserts, rivets, nuts and bolts, or by molding in interlocking configurations directly into the parts, such as in snap-fits.

mechanical properties Properties describing the reaction of physical systems to stress and strain.

mechanical recycling A plastics recycling method in which waste materials are separated, cleaned, shredded, melted, and regranulated for use in new products. The polymeric structure of the material is retained. Separation of plastics into substantially single-variety fractions is usually necessary for high-quality recycled resins; mechanical recycling is most economically viable for plastic components from a single type of plastic, such as LDPE films. Also called material recycling. *See also feedstock recycling, thermal recycling.*

mechanical strain *See strain.*

medium glass fiber *See chopped glass fiber.*

megarad One rad is equivalent to an energy absorption per unit mass of 0.01 joule per kilogram of irradiated material; one megarad is 1E+06 rads. Also called Mrad.

melt blown fiber process A one-step process for manufacturing nonwoven fabric from plastic resin. Extruded, discontinuous filaments are stretched and oriented using a high velocity stream of heated air; fabric is formed by blowing the fibers onto a mesh belt, forming a web that is then stabilized. Melt blowing is a type of air attenuated fiber process. It is similar to spun bonding but uses discontinuous filaments instead of continuous filaments. Melt blown fibers are much finer than spun bonded fibers,

with a typical diameter of 3 μm , and webs are weak and easily distorted. See also spun bonded fiber process.

melt flow index *See melt index.*

melt flow rate *See melt index.*

melt index The amount, in grams, of a thermoplastic polymer which can be forced through an orifice of 0.0825 in. diameter when subjected to a force of 2160 gf in 10 min at 190°C. The test is performed by an extrusion rheometer described in ASTM D1238. Also called MI, MFR, MFI, melt flow rate, melt flow index, base resin melt index.

melting point The temperature at which the solid crystalline and liquid phases of a substance are in thermodynamic equilibrium. The melting point is usually referred to normal pressure of 1 atm.

metallocene catalyst An organometallic catalyst used in the polymerization of polypropylene. It has a sandwich-like structure consisting of a transition metal such as zirconium situated between two cyclic organic compounds. Metallocene catalysts are single-sited and can produce polymers with very narrow molecular weight distributions and lower melting points than conventional polymers. See also catalyst, Ziegler-Natta catalyst, stereospecific catalyst.

methyl group *See alkyl group.*

methyl methacrylate ($\text{CH}_2\text{C}(\text{CH}_3)\text{COOCH}_3$) A colorless, volatile liquid; melts at -48.2°C (-54.8°F) and boils at 101°C (214°F). Soluble in most organic solvents; slightly soluble in water. Easily polymerized by light, heat, ionizing radiation and chemical catalysts; can be copolymerized by other methacrylate esters or other monomers. Its TLV is 100 ppm in air. It is flammable; explosive limit in air is 2.1–12.5%. Derived from oxidation of tert-butyl alcohol first to methacrolein then to methacrylic acid, followed by reaction with methanol, or from reaction of methanol, acetone cyanohydrin and dilute sulfuric acid. Used as a monomer for polymethacrylate and acrylic resins.

methylene oxide *See ethylene oxide.*

MFI *See melt index.*

MFR *See melt index.*

MI *See melt index.*

mica Mica is a crystalline platy filler made by wet or dry grinding of muscovite or phlogopite, minerals consisting mainly of aluminum and potassium orthosilicates, or by chemical reaction between potassium fluorosilicate and alumina. Used as a filler in thermosetting resins to impart good dielectric properties and heat resistance, and in thermoplastics such as polyolefins to improve dimensional stability, heat resistance, and mechanical strength. Mica fillers also reduce vapor permeability and increase wear resistance. Mica fillers having increased flake size or platiness increase flexural modulus, strength, heat deflection temperature, and moisture resistance. Surface modified grades of mica are available for specialty applications.

micron A unit of length equal to $1\text{E}-6$ meter. Its symbol is Greek small letter μ or mum .

microwave welding A welding technique in which high frequency electromagnetic radiation, usually 2–10 GHz, is used to heat a susceptor material placed at the joint in-

terface. Heat conduction from the susceptor to the joint interface melts the thermoplastic parts, and the molten polymers diffuse together, forming a weld after cooling.

migration A mass-transfer process in which the matter moves from one place to another usually in a slow and spontaneous fashion. In plastics and coatings, migration of pigments, fillers, plasticizers and other ingredients via diffusion or floating to the surface or through interface to other materials results in various defects called blooming, chalking, bronzing, flooding, bleeding, etc.

milled glass fiber *See milled glass filler.*

milled glass filler Milled glass fillers are made by hammer milling continuous glass strands. Used as anticrazing reinforcing fillers for adhesives and in plastics. Also called milled glass fiber.

mineral filler Mineral fillers are a large subclass of inorganic fillers comprised of ground rocks or natural or refined minerals. Some fillers, so-called commodity minerals, are relatively inexpensive and are used mostly as extenders. A good example of these is ground limestone. Other fillers, so-called specialty minerals, are usually reinforcing fillers. These are inherently small particle size fillers, such as talc, and surface chemically modified fillers. See also organic filler.

miscible A chemical property in which each of two phases is capable of dissolving in the other.

modulus of elasticity The ratio of unit stress to the unit if deformation of an elastic material below the proportional limit. It gives an indication of a material's stiffness. Also called elasticity constant.

modulus of rupture *See flexural strength.*

molded threaded fastener A fastener or insert, usually metal, that is molded into the part during the molding process. The outside surface can be smooth, knurled, or grooved. The inside surface is threaded to allow insertion of a machine screw.

molded-in insert A method of mechanical fastening in which an insert, usually metal, is molded into one of the parts to be joined. The insert is internally threaded to accept a machine screw, and knurls and grooves on the outer surface of the insert provide pull-out and rotation resistance. Molded-in inserts create high stress in the material around the insert.

molded-in thread A mechanical assembly method in which internal or external threads are molded into plastic parts.

mold shrinkage The difference between the dimension(s) of the mold cavity at 23 C and the dimension(s) of specimen molded. Measured for plastics after cooling the molding to room temperature according to ASTM D955.

molecular weight The molecular weight (formula weight) is the sum of the atomic weights of all the atoms in a molecule (molecular formula). Also called MW, formula weight, average molecular weight.

molecular weight distribution The relative amounts of polymers of different molecular weights that comprise a given specimen of a polymer. It is often expressed in terms of the ratio between weight- and number-average molecular weights, Mw/Mn .

molybdate orange *See coated molybdate orange pigment.*

monofilament A single fiber or filament, produced by extrusion. Monofilaments are stiff and are commonly used in the production of rope and twine.

monomer The individual molecules from which a polymer is formed, i.e. ethylene, propylene.

Mrad *See megarad.*

multifilament In textiles, a fiber or yarn composed of several individual filaments, each of 75 denier or less, that are gathered into a single continuous bundle.

multilayer film A thermoplastic film consisting of two or more different or similar films jointed together, e.g., by coextrusion or lamination, to attain special properties uncharacteristic for a conventional film.

MW *See molecular weight.*

N

nanometer A unit of length equal to 1E-9 meter. Often used to denote the wavelength of radiation, especially in UV and visible spectral region. Also called nm.

near field Refers to the distance that ultrasonic energy is transmitted from the horn to the joint interface in ultrasonic welding. Near field welding occurs when the joint is 0.25 in. (6.4 mm) or less from the point at which the horn contacts the part. See also far field.

neoprene *See neoprene rubber.*

neoprene rubber Generic name for synthetic rubbers made from polymers of chloroprene. They are noted for their good resistance to oil, solvents, heat, sunlight, ozone, and weathering. Most types may be vulcanized to tough products without the use of sulfur. Also called polychloroprene, neoprene, chloroprene rubber.

nest *See fixture.*

nodal point In ultrasonic welding, the point or points in a booster or horn where little or no linear motion occurs.

noncontact hot tool welding A form of heated tool welding in which parts are placed very near the hot tool but are not in direct contact with it. Heat is transferred to the part surfaces by radiation and convection. The hot tool is removed when melting occurs, and parts are then pressed together for cooling and solidification. Used for high temperature polymers when high melting temperatures prohibit the use of non-stick coatings on the hot tool surface. See also heated tool welding, direct contact hot tool welding

nonpolar In molecular structure, a molecule in which positive and negative electrical charges coincide. Most hydrocarbons, such as polyolefins, are nonpolar.

notch effect The effect of the presence of specimen notch or its geometry on the outcome of a test such as an impact strength test of plastics. Notching results in local stresses and accelerates failure in both static and cycling testing (mechanical, ozone cracking, etc.).

notched Izod impact strength *See Izod impact energy.*

notched Izod strength *See Izod impact energy.*

nucleated polypropylene Nucleated polypropylene is a polypropylene thermoplastic which contains nucleating agents to accelerate the crystallization during injection molding. Faster crystallization leads to improved clarity, fewer sink marks, and shorter molding cycle. Nucleated PP has low density and good flexibility and resistance to chemicals, abrasion, moisture, and stress cracking, but decreased dimensional stability, mechanical strength, and resistance to UV light and heat. Nucleated PP is flammable. Processed by blow and injection molding, extrusion, and thermoforming.

nm *See nanometer.*

nucleating agent A chemical substance added to a plastic that provides nuclei for crystal growth. Addition of nucleating agents produces a more uniform crystalline structure and a higher degree of crystallinity. Examples of nucleating agents used in polypropylene processing include benzoic acid and adipic acid and their metal salts. See also nucleated polypropylene.

nylon Nylons are thermoplastic, mostly aliphatic polyamides prepared usually either by polymerization of dicarboxylic acid with diamine, or polymerization of amino acid, or ring opening polymerization of lactam. Nylons have good resistance to solvents, bases, and oils; to impact; abrasion; and creep. They have also high tensile strength and barrier properties, and a low coefficient of friction. The disadvantages include high moisture pickup, light degradation, and high mold shrinkage. Processing is achieved by injection, blow, and rotational molding; extrusion; and powder coating. Uses are automotive parts, electrical and electronic devices such as plugs, machine parts such as gears and pumps, housings for appliances and power tools, wire and cable jacketing, pipes, films, and fibers.

O

olefinic plastic *See polyolefin.*

olefinic resin *See polyolefin.*

olefinic thermoplastic elastomer Olefinic thermoplastic elastomers are usually continuous blends of EPDM or EPR rubbers with polypropylene or polyethylene, which are sometimes crosslinked. They have low specific gravity, good resistance to weak acids and bases and to polar solvents, excellent dielectric properties, wide range of mechanical properties, and good (re)processability. The negatives include poor oil resistance and flammability. Blended materials have low compression set at elevated temperatures, where as crosslinked materials have good compression set but cost more. Processed by extrusion, injection and blow molding, thermoforming, and calendaring. Applications include automotive parts, building materials (e.g., weather stripping), wire and cable jacketing, and sporting goods. Also called TPO, thermoplastic polyolefin rubber, thermoplastic olefinic rubber, TEO, polyolefin thermoplastic rubber, olefinic TPE, olefinic thermoplastic rubber.

olefinic thermoplastic rubber *See olefinic thermoplastic elastomer.*

olefinic TPE *See olefinic thermoplastic elastomer.*

one-part adhesive An adhesive that does not require a separate hardener or catalyst for bonding to occur. Types of one-part adhesives include UV curing, curing, emulsion, solvent, and water-activated. UV curing adhesives cure only by application of ultraviolet light; other curing one-part adhesives contain an integral catalyst or hardener with a degree of latency, so that cure at either room temperature or elevated temperature is possible. These curing adhesives must be refrigerated during storage and can have unpredictable curing behavior; examples are a liquid epoxy and dicyandiamide hardener, aerobic adhesives that require oxygen or moisture for activation, or silicone adhesives that require moisture. Emulsion adhesives are thermoplastics or elastomers dispersed in an aqueous phase, such as a copolymer of vinyl acetate and ethylene; one substrate must be permeable to allow escape of water from the system. Solvent adhesives are solutions or pastes of thermoplastics or elastomers in organic or water solvents. Water-activated adhesives, based on starch, cellulose, or protein, are dry powders that must be mixed with water for activation; adhesive strength develops when water is lost, so that usually one substrate must be permeable. *See also* two-part adhesive.

optical properties The effects of a material or medium on light or other electromagnetic radiation passing through it, such as absorption, reflection, etc.

orientation A process of drawing or stretching of as-spun synthetic fibers or hot thermoplastic films to orient polymer molecules in the direction of stretching. The fibers are drawn uniaxially and the films are stretched either uniaxially or biaxially (usually longitudinally or longitudinally and transversely, respectively.) Oriented fibers and films have enhanced mechanical properties. The films will shrink in the direction of stretching, when reheated to the temperature of stretching.

organic compound A chemical compound that contains one or more carbon atoms in its molecular structure.

organic filler Organic fillers are made from natural or synthetic organic materials. Natural material derived organic fillers include wood and shell flours. Synthetic material derived fillers include fluoropolymer spheres and milled polymer waste. Organic fillers are characterized by relatively low cost and low density. They might increase the flammability and decrease the moisture resistance of plastics. *See also* mineral filler.

organometallic compound A chemical compound in which carbon is bonded to a metal. Many organometallic compounds are used as catalysts in polymerization reactions.

orientation Realignment of the molecular configuration of a plastic produced by stretching while it is still hot. *See also* biaxial orientation.

oven stability *See thermal stability.*

oxidizing agent A substance that causes the removal of electrons (oxidation) from another substance. The oxidizing agent is reduced during the reaction.

oxirane *See ethylene oxide.*

P

PA *See polyamide.*

Pa *See pascal.*

parison In blow molding, a hollow tube of thermoplastic melt which is expanded by air pressure to the shape of the mold cavity.

particulate filler A material in the form of small particles added to a plastic to alter its physical, mechanical, thermal, electrical, or other properties or to decrease cost. Sometimes used to refer to mineral but not glass particles.

parts per hundred A relative unit of concentration, parts of one substance per 100 parts of another. Parts can be measured by weight, volume, count or any other suitable unit of measure. Used often to denote composition of a blend or mixture, such as plastic, in terms of the parts of a minor ingredient, such as plasticizer, per 100 parts of a major, such as resin. Also called phr.

parts per hundred million A relative unit of concentration, parts of one substance per 100 million parts of another. Parts can be measured by weight, volume, count or any other suitable unit of measure. Used often to denote very small concentration of a substance, such as impurity or toxin, in a medium, such as air. Also called ppm.

parylene Thermoplastics made by vapor-phase polymerization of p-xylene. Hot p-xylene vapors are cooled to condense the monomer and deposit it as a polymer in the form of a thin, uniform coating on a substrate such as paper or fabric.

pascal An SI unit of measurement of pressure equal to the pressure resulting from a force of one newton acting uniformly over an area of one square meter. Used to denote the pressure of gases, vapors or liquids and the strength of solids. Also called Pa.

PBT *See polybutylene terephthalate.*

PBTR *See polybutylene terephthalate.*

PC *See polycarbonate.*

PCTFE *See polychlorotrifluoroethylene.*

PE *See polyethylene.*

PEEK *See polyetheretherketone.*

PEI *See polyetherimide.*

PEK *See polyetherketone.*

pendant methyl group A methyl (CH₃) functional group attached to the main chain of a polymer molecule.

permeability The capacity of material to allow another substance to pass through it; or the quantity of a specified gas or other substance which passes through under specified conditions.

permittivity loss factor *See dielectric dissipation factor.*

PET *See polyethylene terephthalate.*

PETG *See polycyclohexylenedimethylene ethylene terephthalate.*

PETR *See polyethylene terephthalate.*

phenol formaldehyde resin *See phenolic resin.*

phenolic *See phenolic resin.*

phenolic resin Thermoset phenolics are prepared by reacting phenols with excess or less than the stoichiometric amount of aldehydes such as formaldehyde in the presence of base or acid catalysts to give resole or novolak resins, respectively. The resins are soluble and heat curable. Novolak resins require a bifunctional crosslinking agent, usually diamine, to cure. Uncured or partially cured resins are used as coatings, adhesives, potting compounds, and binders. Cured resins are characterized by good dielectric properties, hardness, thermal stability, rigidity, and compressive strength but poor resistance to bases and oxidizers and dark color. Filled or reinforced phenolic powders can be processed by compression, transfer, or injection molding and extrusion. Molding uses include handles, electrical devices, and automotive parts. Also called phenolic, phenol formaldehyde resin, PF.

photolysis Decomposition or alteration of a chemical compound by exposure to radiant energy.

phr *See parts per hundred.*

physical adsorption *See adsorption.*

PI *See polyimide.*

piezoelectric material A material, such as ceramic, that changes dimensions when voltage is applied, or produces voltage (electrical potential) when deformed. Used to convert mechanical energy into electrical energy and vice versa.

pitch diameter The average between the major (outside) and minor (root) diameter of a thread. For practical purposes, this diameter is assumed to be equal to the diameter of the smooth shaft prior to threading.

plasma arc treatment In adhesive and solvent bonding, a method for treating the surfaces of parts prior to solvent and adhesive bonding, in which an electrical current between two electrodes in a gas at low pressure excites the gas particles, producing free radicals. Contaminants are stripped from the surface of the part, and wettability is increased by reduction of the contact angle. Also called plasma discharge, plasma treatment. See also corona discharge treatment.

plastic *See polymer.*

plasticizer A substance incorporated into a material such as plastic or rubber to increase its softness, processability and flexibility via solvent or lubricating action or by lowering its molecular weight. Plasticizers can lower melt viscosity, improve flow and increase low-temperature resilience of material. Most plasticizers are nonvolatile organic liquids or low-melting-point solids, such as dioctyl phthalate or stearic acid. They have to be non-bleeding, nontoxic and compatible with the material. Sometimes plasticizers play a dual role as stabilizers or crosslinkers.

PMMA *See polymethyl methacrylate.*

pneumatic Air-powered, operated, or controlled.

polar In molecular structure, a molecule in which the positive and negative electrical charges are permanently separated. Polar molecules ionize in solution and impart electrical conductivity to the solution. Water, alcohol, and sulfuric acid are polar molecules; carboxyl and hydroxyl are polar functional groups.

polyacrylate *See acrylic resin.*

polyallomer Crystalline thermoplastic block copolymers of ethylene, propylene, and sometimes other unsaturated monomers. Produced by anionic coordination polymerization. Have high impact strength, low density, and flex life.

polyamide Thermoplastic polymers prepared usually by either polymerization of dicarboxylic acid with diamine, or polymerization of amino acid, or ring opening polymerization of lactam. Polyamides are characterized by the presence of backbone amide groups and can be aromatic (aramids) or aliphatic (nylons). Characterized by outstanding mechanical properties, chemical resistance, and antifriction properties. Processed by extrusion and molding. Used as reinforcement and textile fibers, machine parts, and coatings. Also called polyamide resin, polyamide plastic, PA.

polyamide plastic *See polyamide.*

polyamide polyimide *See polyimide.*

polyamide resin *See polyamide.*

polyamide thermoplastic elastomer These thermoplastic elastomers are mostly copolymers containing soft polyether and hard polyamide blocks. Have improved chemical, abrasion, and thermal resistance and good impact strength and elongation. Processed by extrusion and injection and blow molding. Used in sporting goods, automotive and electrical applications, brushes, and bel-lows. Also called thermoplastic polyamide rubber, polyamide TPE, polyamide thermoplastic rubber.

polyamide thermoplastic rubber *See polyamide thermoplastic elastomer.*

polyamide TPE *See polyamide thermoplastic elastomer.*

polyamideimide *See polyimide.*

polyaniline A family of polymers that exists in three different oxidation states at the molecular level: leuco-emeraldine (fully reduced), emeraldine (half-oxidized), and pernigraniline (fully oxidized). The polyaniline emeraldine base becomes electrically conductive when doped with aqueous protonic acids, such as HCl. Conductivity is dependent on the morphology of the polyaniline. For high conductivity, polyaniline is spun into fibers with high crystallinity and orientation.

polyaryl ether *See polyphenylene ether.*

polyaryl oxide *See polyphenylene ether.*

polyarylamide Thermoplastic aromatic polyamide prepared by polymerization of aromatic diamine and aromatic diacid or its derivatives (e.g., anhydride). These plastics are characterized by high heat resistance, good retention of mechanical and dielectric properties at elevated temperatures, good dielectric properties, chemical resistance, high stiffness, and low flammability. High crystallinity results in good mechanical properties such as impact strength. Resistance to light is somewhat low. Processing is difficult because of high melting point. Processed by solution casting, molding, and extrusion. Uses include film, fibers, and molded parts requiring good surface finish. Also called PARA, aromatic polyamide, aramid.

polyarylene ether *See polyphenylene ether.*

polyarylene oxide See *polyphenylene ether*.

polyarylsulfone Polyarylsulfone is a thermoplastic containing repeating sulfone and ether groups in its wholly aromatic backbone. It has excellent resistance to high and low temperatures, good impact strength, improved resistance to environmental stress cracking, good dielectric properties, rigidity, and resistance to acids and alkalis. Polyarylsulfone is nonflammable, but is attacked by some organic solvents. Processed by injection molding, compression molding, and extrusion. Used in high temperature electrical and electronic applications such as circuit boards and lamp housings, piping, and auto parts.

polybutylene terephthalate PBT is a saturated polyester thermoplastic prepared by transesterification of dimethyl terephthalate with butanediol during melt polycondensation. PBT has good tensile strength, dielectric properties, and chemical resistance, except for resistance to strong bases and halogenated solvents. Water absorption of PBT is very low. The material has a relatively low Izod impact strength and thermal stability, but these can be easily overcome by proper modification. Processed by injection and blow molding, extrusion, and thermoforming. Used in automotive body parts, electrical switches and relays, household appliances, and housings for power tools and various consumer products. Also called polytetramethylene terephthalate, PBTR, PBT.

polycarbodiimide Polymers containing $-N=C=N-$ linkages in the main chain, typically formed by catalyzed polycondensation of polyisocyanates. They are used to prepare open-celled foams with superior thermal stability. Sterically hindered polycarbodiimides are used as hydrolytic stabilizers for polyester-based urethane elastomers.

polycarbonate Polycarbonates are thermoplastics prepared by either phosgenation of dihydric phenols such as bisphenol A or by ester exchange between diaryl carbonate, usually diphenyl carbonate, and dihydric phenol. They are characterized by the presence of repeating carbonyldioxy groups in the backbone, but classified by some as polyesters. They have very good mechanical properties, especially impact strength, low moisture absorption, and good thermal and oxidative stability. They are self-extinguishing and some grades are transparent; but are attacked by strong acids and bases, soluble in organic solvents, and subject to stress cracking. Processed by injection and blow molding, extrusion, thermoforming, but require high processing temperatures. Used in telephone parts, dentures, business machine housings, safety equipment, nonstaining dinnerware, and food packaging. Also called PC.

polychloroprene See *neoprene rubber*.

polychlorotrifluoroethylene Thermoplastic prepared by radical polymerization of chlorotrifluoroethylene. It has good transparency and great barrier properties. Dielectric properties and resistance to solvents, especially chlorinated, of CTFE are somewhat lower than those of perfluoropolymers, but tensile strength and creep resistance are higher. Processing is difficult, because of high melt viscosity, but possible by extrusion, injection molding, compression molding, and coating. Uses include chemical apparatus, cryogenic seals, films, and coatings. Also, CTFE spheres are used as fillers

and CTFE oil is used as a lubricant in various plastics. Also called PTFCE, PCTFE, CTFE.

Polycyclohexylenedimethylene ethylene terephthalate

PETG is a thermoplastic polyester prepared by polycondensation of cyclohexylenedimethylenediol, ethylene glycol, and terephthalic acid. Processed by injection and blow molding and shape, tubing, film and sheet extrusion. It is an amorphous, clear polymer having high stiffness and hardness and good toughness even at low temperatures. PETG is FDA approved. Applications include containers for cosmetics and foods, packaging film, medical devices, instrument covers, machine guards and toys. Also called PETG.

Polycyclohexylenedimethylene terephthalate PCT is a thermoplastic polyester which can be prepared by polycondensation of cyclohexylenedimethylenediol and terephthalic acid. It is usually filled with glass fiber for high-heat applications. Processed by molding and extrusion. Also called PCT.

polyester A large class of polymers usually made by polycondensation of polyol with polycarboxylic acid or anhydride, or polycondensation of hydroxycarboxylic acid. Polyesters are characterized by the presence of a repeating carbonyloxy group in the backbone and can be aliphatic or aromatic. There are thermosetting polyesters consisting of alkyd resins and unsaturated polymers, and thermoplastic polyesters including elastomers. The properties, processing techniques, and applications of polyesters vary widely. Also called copolyester.

polyester terephthalate See *terephthalate polyester*.

polyester thermoplastic elastomer These thermoplastic elastomers are mostly copolymers containing soft polyether and hard polyester blocks. They have a broad flexibility/stiffness spectrum, good dielectric strength, chemical resistance, exceptional dynamic performance, superior appearance, good creep resistance, and excellent retention of properties at temperatures ranging from -40 to $+300^{\circ}\text{F}$, but require protection from ultraviolet radiation. Processed by injection, blow, and rotational molding, extrusion casting, and film blowing. Uses include electrical insulation, medical products, exterior automotive parts, business equipment, and consumer goods. Also called TEEE, polyester TPE, polyester thermoplastic rubber, copolyester TPE, copolyester thermoplastic rubber.

polyester thermoplastic rubber See *polyester thermoplastic elastomer*.

polyester TPE See *polyester thermoplastic elastomer*.

polyether polyimide See *polyetherimide*.

polyether polysulfone See *polyethersulfone*.

polyetheretherketone Polyetheretherketone is a partially crystalline thermoplastic containing repeating ether and keto groups in the backbone. Its systematic name is poly(oxy-1,4-phenyleneoxy-1,4-phenylenecarbonyl-1,4-phenylene). PEEK has superb chemical resistance, toughness, rigidity, load-bearing properties, thermal stability, radiation resistance, and very low flammability. Processed readily by injection molding, spinning, cold forming, and extrusion. Used in fibers, films, automotive engine parts, aerospace composites, and wire and cable insulation. Also called PEEK.

polyetherimide Polyetherimides are thermoplastics containing repeating cyclic imide and ether groups in the backbone. They are prepared by cyclopolycondensation of diether dianhydrides such as that of benzoic acid and bisphenol A, and aromatic diamine. Polyetherimides have good chemical resistance, thermal and hydrolytic stability, and good dielectric properties and resistance to creep at elevated temperatures. Processed by extrusion, thermoforming, compression molding, injection molding, blow molding, and film techniques. Used in automotive parts, jet engine components, surgical instruments, industrial fluid and air handling components, food packaging, cookware, and computer disks. Also called polyether polyimide, PEI.

polyetherketone Thermoplastic with excellent high-temperature properties and thermal stability. Used in advanced composites, wire coating, chemical-resistant filters, integrated circuit wafer carriers, and bearings. Synthesized by polyarylation or polyetherization. Also called PEK.

polyethersulfone Polyethersulfone is a thermoplastic containing repeating sulfone and ether groups in its wholly aromatic backbone. It has excellent thermal stability in air and water, good transparency, very low flammability and smoke emission, good dimensional stability, rigidity, and toughness. It has low mold shrinkage and is a good, heat-resistant dielectric. Polyethersulfone has good resistance to acids and bases but is attacked by many organic solvents, has poor weatherability, and is subject to stress cracking. Processed by injection molding, extrusion, blow molding, and compression molding; but requires high processing temperatures. Used in high temperature electrical applications such as multipin connectors, bakery oven windows, medical devices, radomes, structural aircraft components, appliance housings, and auto parts. Also called polyether polysulfone, PESV.

polyethylene A family of polyolefins consisting of linear and branched polyethylenes. Polyethylenes are thermoplastics but can be crosslinked by irradiation or chemically and then show improved strength and dielectric properties. All linear polyethylenes, except the high density grade, are prepared by copolymerization of ethylene with higher olefins. Branched polyethylenes are prepared from ethylene alone or together with polar comonomers such as vinyl acetate. The density, melt index, crystallinity, degree of branching, molecular weight, polydispersity, and related properties of polyethylenes vary widely depending on the catalysts and methods of polymerization and on modifying comonomers and treatments. Polyethylenes have good impact resistance at low temperatures, good chemical resistance, and good moisture resistance, but high thermal expansion, poor weatherability, poor thermal stability and resistance to stress cracking. They are readily processable by all thermoplastic methods but are flammable and difficult to bond. Food grades are available. Processed by extrusion, blow and injection molding, thermoforming. Used very broadly as films, coatings, in containers and consumer goods, electrical insulation, and piping. Also called PE, expandable polyethylene bead, EPE bead.

polyethylene copolymer PE copolymers are thermoplastics prepared by copolymerization of ethylene with other olefins such as propylene. Processed by molding and extrusion.

polyethylene glycol terephthalate See *polyethylene terephthalate*.

polyethylene terephthalate PET is a saturated polyester thermoplastic prepared by polycondensation of ethylene glycol with terephthalic acid or its dimethyl ester. PET is extremely hard, wear resistant, dimensionally stable, resistant to chemicals, and has good dielectric properties. Its tensile strength and thermal stability improve dramatically with increasing crystallinity and orientation. PET is processed by high temperature extrusion, injection and blow molding, melt spinning, and film extrusion. Uses include fiber, FDA approved film for food packaging, beverage bottles, magnetic tapes, photographic films, and food trays. Also called polyethylene glycol terephthalate, PETR, PET.

polyimide Thermoplastic aromatic polyimides (polyamide-imides) are normally made in a two step process by polymerizing trimellitic anhydride with an aromatic diamine to form a polyamic acid containing amide groups in the backbone and pendant carboxyl groups, followed by cyclocondensation of carboxyl and amide groups to form imide groups. They are characterized by superior tensile and compressive strengths at temperatures up to 500°F with good dimensional stability and creep, impact, and chemical resistance. High thermal stability of polyamide imides is complimented by low flammability and good adhesive, dielectric, and barrier properties. On the other hand, polyamide-imides have poor processability, due to their highly viscoelastic behavior in the melt, and poor resistance to alkali. Processing is achieved by compression and injection molding, and various powder sintering, film casting and solution coating techniques. Thermoset polyimides are usually supplied as polyamic acids and require curing at elevated temperatures. The properties of thermoset polyimides are similar to those of thermoplastic polyimides. Thermoset polyimides have good processability due to their low melt viscosity. They are processed by transfer and injection molding, lamination, and coating. Uses of both thermoset and thermoplastic polyimides include jet engine components, compressor parts, electronic coatings, automotive parts such as seal rings in transmissions, and business machine parts. Also called polyamideimide, polyamide polyimide, PI, PAI, amideimide resin.

polyketone Polyketones are a class of thermoplastics, the most important representatives of which are polyetherketone and polyetheretherketone. Characterized by the presence of repeating keto groups in the backbone. Also called ketone resin.

polymer Polymers are high molecular weight substances with molecules resembling linear, branched, crosslinked, or otherwise shaped chains consisting of repeating molecular groups. Synthetic polymers are prepared by polymerization of one or more monomers. The monomers comprise low-molecular-weight reactive substances, often containing >1 reactive molecular bond or chemical bond. Natural poly-

mers have molecular structures similar to synthetic polymers but are not man made, occur in nature, and have various degrees of purity. Also called synthetic resin, synthetic polymer, resin, plastic.

polymeric foam A plastic with numerous cells disposed through its mass. Produced by incorporating a blowing agent which decomposes to liberate a gas, mechanically stirring in a fluid or gas, or adding a water-soluble salt or other solvent-soluble agent prior to forming and then leaching out the agent after forming to leave voids. Used in low-weight articles, heat insulation and packaging.

polymethyl methacrylate An acrylic resin that is made by polymerizing the monomer methyl methacrylate. Good optical clarity (92% light transmission), excellent resistance to weathering, good impact strength and electrical properties, non-toxic, tasteless. Powders can be injection molded, extruded, and compression molded. Liquid can be cast into rods, sheets, lenses. Used in airplane canopies, signs, lighting fixtures. Also called PMMA.

polymethylpentene Polymethylpentene is a thermoplastic polyolefin prepared by Ziegler copolymerization of 4-methyl-1-pentene. It has very low density (0.83 g/cm³); high light transmission; high melting point; good rigidity, dielectric, and tensile properties and chemical resistance. Processed by injection molding, extrusion, and blow molding. Used in laboratory ware, extrusion-coated paper, high-intensity light fixtures, automotive parts such as radiator plugs, sight glasses, wire insulation, and small appliances. Also called PMP.

polyolefin Polyolefins are a large class of carbon-chain elastomeric and thermoplastic polymers usually prepared by addition (co)polymerization of olefins or alkenes such as ethylene. The most important representatives of this class are polyethylene and polypropylene. There are branched and linear polyolefins and some contain polar pendant groups or are halogenated. Unmodified polyolefins are characterized by relatively low thermal stability and a nonporous, nonpolar surface with poor adhesive properties. Processed by extrusion, injection molding, blow molding, and rotational molding. Other thermoplastic processes are used less frequently. This class of plastics is used more and has more applications than any other. Also called olefinic resin, olefinic plastic.

polyolefin thermoplastic rubber *See olefinic thermoplastic elastomer.*

polyphenylene ether PPE are amorphous thermoplastics containing repeating ether groups in the backbone. They are prepared by oxidative polycondensation of substituted phenols such as 2 and are characterized by a wide range of service temperatures and excellent dielectric properties and resistance to acids and bases. They have outstanding impact and fatigue strength and resistance to radiation and oxidation. They are miscible with polystyrene and other polymers in a wide range of ratios and are used usually in modified or alloyed form. Processed by extrusion and injection molding. Used in automotive parts, battery cases for aerospace use, and appliances. Also called PPO, PPE, polyphenylene oxide, polyarylene oxide, polyarylene ether, polyaryl oxide, polyaryl ether.

polyphenylene oxide *See polyphenylene ether.*

polyphenylene sulfide PPS is a high-performance engineering thermoplastic. Its linear chains consist of benzene rings para-substituted with sulfur atom links. PPS has excellent thermal stability; good resistance to solvents and chemicals, except for chlorinated hydrocarbons; good radiation resistance; excellent dimensional stability; low water absorption; and good dielectric properties, but somewhat low impact strength. PPS is nonburning. Processing of PPS is hampered by its high melting point and is achieved at elevated temperatures by injection molding, compression molding, transfer molding, and extrusion. Used in hydraulic components, bearings, valves, electronic parts, small appliances such as hair dryers, and under-the-hood automotive parts. Also, PPS spheres are used as fillers in various plastics. Also called polythiophenylene.

polyphenylene sulfide sulfone Thermoplastic with good thermal stability, chemical resistance, and dielectric properties and low flammability and creep. Processed by injection molding. Used in electrical components. Also called polyphenylenesulfidesulfone.

polyphenylenesulfidesulfone *See polyphenylene sulfide sulfone.*

polyphthalamide Thermoplastic aromatic polyamide prepared by polymerization of aromatic diamine and phthalic acid or its derivatives (e.g., anhydride). These plastics are characterized by high heat resistance, good retention of mechanical and dielectric properties at elevated temperatures, good dielectric properties, chemical resistance, high stiffness, and low flammability. High crystallinity results in good mechanical properties such as impact strength. Resistance to light is somewhat low. Processing is difficult because of high melting point. Processed by solution casting, molding, and extrusion. Uses include film, fibers, and molded parts requiring good surface finish. Also called PPA.

polypropylene PP is a carbon chain thermoplastic comprised of propylene homopolymer prepared by stereospecific polymerization in the presence of Ziegler Natta catalysts. The majority of PP is isotactic. PP has low density and good flexibility and resistance to chemicals, abrasion, moisture, and stress cracking, but decreased dimensional stability, mechanical strength, and resistance to UV light and heat. PP is flammable. Processed by injection molding, spinning, extrusion, and film techniques. Used as films for pressure sensitive tapes, packaging, liners, and shrink films, and as fibers in textiles. Also called PP homopolymer, PP, polypropylene homopolymer, expandable polypropylene bead, EPP bead.

polypropylene homopolymer *See polypropylene, homopolymer.*

polypyrrole A polymer of pyrrole, a five-membered heterocyclic substance with one nitrogen and four carbon atoms and with two double bonds. The polymer can be prepared via electrochemical polymerization. Polymers thus prepared are doped by electrolyte anion and are electrically conductive. Polypyrrole is used in lightweight secondary batteries, as electromagnetic interference shielding, anodic coatings, photoconductors, solar cells, and transistors.

polysiloxane *See silicone.*

polystyrene Polystyrene is a thermoplastic produced by homopolymerization of styrene. It has good rigidity, high dimensional stability, low moisture absorption, optical clarity, high gloss, and good dielectric properties. On the other hand, it is flammable, has poor impact strength and resistance to solvents, heat, UV radiation, and chemicals. Processed by injection molding, extrusion, compression molding, and foam molding. Used widely in medical devices, household items such as cutlery handles and housewares, food packaging, electronics, and foam insulation. Also called polystyrol, expandable polystyrene bead, EPS bead, crystal polystyrene.

polystyrol *See polystyrene.*

polysulfide Polysulfides are a large class of polymers containing repeating thio linkages in the aromatic, alicyclic, or aliphatic backbone. The most important families of polysulfides are polythiophenylenes and sulfide rubber. The former resemble polyethers with sulfur substituting oxygen, whereas the latter has usually a series of connected sulfur atoms in the repeating unit.

polysulfide adhesive Flexible, one- or two-part adhesives that cure by a crosslinking reaction. Also called sulfide adhesive.

polysulfone Polysulfones are a class of thermoplastics characterized by the presence of sulfone linkages in their repeating units. Most polysulfones are aromatic and also contain ether linkages to enhance oxidation resistance. The most important of those are polyarylsulfone and polyethersulfone. As a class, polysulfones show excellent thermal stability, low creep, good dielectric properties, transparency, self extinguishing properties, and resistance to chemicals, but are attacked by many solvents, have poor weatherability, are subject to stress cracking, and require high processing temperatures. Processed by injection molding, compression molding, blow molding, and extrusion. Used in appliances, electronics, automotive parts, and electric insulators. A high-performance engineering thermoplastic, called polysulfone in the trade, consists of diaryl sulfone groups linked by oxygen atoms and shares many properties typical for its class. It has good rigidity at elevated temperatures, good impact strength, and resists alkalis and acids but is attacked by polar solvents. Used for medical devices, in food processing equipment, electronics, chemical apparatus, and battery cells. Also called PSU, PSO.

polytetrafluoroethylene Thermoplastic prepared by radical polymerization of tetrafluoroethylene. It has low dielectric constant, superior chemical resistance, very high thermal stability, low friction coefficient, excellent antiadhesive properties, low flammability, and high weatherability. Impact resistance of PTFE is high, but permeability is also high whereas strength and creep resistance are relatively low. The very high melt viscosity of PTFE restricts its processing to sinter molding and powder coating. Uses include coatings for cooking utensils, chemical apparatus, electrical and nonstick items, bearings, containers. Also, PTFE spheres are used as fillers and PTFE oil is used as a lubricant in various plastics. Also called TFE, PTFE, modified PTFE.

polytetramethylene terephthalate *See polybutylene terephthalate.*

polythiophenylene *See polyphenylene sulfide.*

polyurethane Polyurethanes (PU) are a large class of polymers, the backbone of which consists of repeating units containing urethane group. PU are usually prepared by interfacial polycondensation of polyisocyanates with polyols. The latter may be based on polyesters or polyethers or both. The most important members of this class are urethane rubbers, nonelastomeric thermoplastic PU, urethane thermoplastic elastomers, and thermoset urethane resins. PU may be rigid or soft and flexible, cellular or solid and offer a wide range of properties depending on composition and molecular structure. In general they have high abrasion resistance, good retention of properties at low temperatures, and good foamability, but poor heat resistance, weatherability, and resistance to solvents. PU are flammable and are made with toxic substances (isocyanates). Nonelastomeric thermoplastic PU are not chemically crosslinked and are processed by injection molding and extrusion. Thermoset PU can be cured at moderate and ambient temperatures and give foams with good heat insulating properties. They are processed mainly by reaction injection molding, various foam techniques, casting, and coating. PU are used in load bearing rollers and wheels, acoustic clamping materials, sporting goods, seals and gaskets, rigid and flexible foams for heat insulation and other uses, potting, and encapsulation. Also called urethane polymer. *See also nonelastomeric thermosetting polyurethane.*

polyurethane adhesive One- or two-part adhesives that cure by a polymerization reaction to form temperature resistant bonds that are both rigid and flexible.

polyurethane thermoplastic rubber *See urethane thermoplastic elastomer.*

polyurethane TPE *See urethane thermoplastic elastomer.*

polyvinyl chloride PVC is a thermoplastic prepared by free-radical polymerization of vinyl chloride in dispersion (emulsion), bulk, or suspension processes. A small amount of comonomer is sometimes added to enhance adhesion or other properties. Unmodified PVC is rigid and requires plasticizers to make it more flexible. The main end forms of PVC are rigid and flexible. The flexible form is often made from plastisols, suspensions of PVC in liquid plasticizers. PVC can be chlorinated to increase its heat deflection temperature and tensile strength and to reduce flammability and smoke generation. PVC is dimensionally stable, largely nonflammable, and resistant to weathering, but has limited thermal stability, high density, and is attacked by many solvents. Processed by injection molding, calendaring, extrusion, powder coating, blow molding, extrusion coating, and film techniques. Used very widely as films, fabric coatings, wire coatings, toys, bottles, and pipes. Also called PVC.

polyvinyl dichloride *See polyvinylidene chloride.*

polyvinylidene chloride A stereoregular, thermoplastic polymer derived by the polymerization of vinylidene chloride or copolymerization of vinylidene chloride with lesser amounts of other unsaturated compounds. This polymer is resistant to

abrasion and chemical attack, impermeable to flavor, and possesses low vapor transmission properties. Uses include packaging for food, insecticide-impregnated multiwall paper bags, pipes for chemical processing equipment, seat covers, upholstery, fibers, bristles, and latex coatings. Also called PVDC, polyvinyl dichloride.

polyvinylidene fluoride Thermoplastic prepared from vinylidene fluoride. It has substantially higher strength, wear resistance, and creep resistance than other fluoropolymers but relatively high dielectric constant and loss factor. PVDF is nonflammable, resists most solvents, and has excellent weatherability. Its service temperature limit and chemical resistance are lower than those of perfluoropolymers. PVDF is processed readily by extrusion, injection molding, transfer molding, and powder or dispersion coating. Uses include electrical insulation, pipes, chemical apparatus, coatings, films, containers, and fibers. Also called VF2, PVF2, PVDF.

powdered carbon *See carbon filler.*

PP *See polypropylene.*

PP homopolymer *See polypropylene.*

PPA *See polyphthalamide.*

PPE *See polyphenylene ether.*

pphm *See parts per hundred million.*

ppm A unit for measuring small concentrations of material or substance as the number of its parts (arbitrary quantity) per million parts of medium consisting of another material or substance.

PPO *See polyphenylene ether.*

press fit *See interference fit.*

pressure sensitive adhesive An adhesive that requires applied pressure on the parts for bonding to occur. Usually composed of a rubbery elastomer and modifying tackifier, pressure sensitive adhesives are applied to the parts as solvent-based adhesives or hot melts; curing does not usually occur. They adhere tenaciously under slight pressure and are highly thixotropic. Disadvantages include limited temperature capability and susceptibility to oxidative degradation. *See also* contact sensitive adhesive.

primer In adhesive bonding, a reactive chemical species dispersed in a solvent that is applied to the part surface by spraying or brushing. After the solvent is flashed off, the part surface may be bonded immediately, as in polyolefin primers for cyanoacrylates, or may require time to react with atmospheric moisture, as in silane and isocyanate-based primers used for silicone and polyurethane-based adhesives, respectively. Primers generally contain a multifunctional chemically reactive species capable of acting as a chemical bridge between the substrate and the adhesive. Primers are commonly used with acetals, fluoropolymers, polybutylene terephthalate, silicone, polyurethane, and polyolefins. In coatings, coatings applied on a substrate prior to subsequent coatings or topcoat in order to seal the pores, improve adhesion of the topcoat, improve corrosion protection, hide surface imperfections or color, etc. Usually based on polymers with functional additives. Applied by the same techniques as coatings. Also called primer coating.

primer coating *See primer.*

process time *See processing time.*

processing agents Agents or media used in the manufacture, preparation and treatment of a material or article to improve its processing or properties. The agents often become a part of the material.

processing defects Structural and other defects in material or article induced inadvertently during manufacturing, preparation and treatment processes by using wrong tooling, process parameters, ingredients, part design, etc. Usually preventable. Also called processing flaw.

processing flaw *See processing defects.*

processing methods Method names and designations for material or article manufacturing, preparation and treatment processes. Note: Both common and standardized names are used.

processing parameters Measurable parameters such as temperature prescribed or maintained during material or article manufacture, preparation and treatment processes.

processing time Time required for the completion of a process in the manufacture, preparation and treatment of a material or article. Also called recommended processing time, process time.

promoter *See accelerator.*

propene *See propylene.*

propylene An alkene (unsaturated aliphatic hydrocarbon) with three carbon atoms, $\text{CH}_2=\text{CHCH}_3$. A colorless, highly flammable gas. Autoignition temperature 497°C . Derived by thermal cracking of ethylene or from naphtha. Used as monomer in polymer and organic synthesis. Also called propene.

PSO *See polysulfone.*

PSU *See polysulfone.*

PU TPE *See urethane thermoplastic elastomer.*

pullout strength The resistance of a screw or insert to forces that tend to pull it out of the part or boss.

pulp *See cellulose.*

PUR TPE *See urethane thermoplastic elastomer.*

PVC *See polyvinyl chloride.*

Q

quencher *See energy quencher.*

R

radiation dosage *See radiation dose.*

radiation dose Amount of ionizing radiation energy received or absorbed by the material during exposure. Also called radiation dosage, ionizing radiation dose.

radiation resistant materials Materials that resist degradation on long- and medium-term or repeated exposure to ionizing radiation, e.g., steel grades designed for nuclear reactors. Radiation damage to materials includes swell-

ling, radiolysis, blistering, changes in electrical and mechanical properties, etc. There are different mechanisms of radiation damage but most can be linked to free-radical reactions. The resistance of materials to radiation can be improved by stabilizing them with agents that can neutralize free radicals, such as dimethyl sulfoxide, carbohydrides and various reducing agents. Also called radiation stabilized material.

radiation stabilized material *See radiation resistant materials.*

radio frequency welding A method of welding thermoplastics that uses a radio-frequency electromagnetic field. (usually 27.1 MHz) to apply the necessary heat. The radio-frequency field is usually applied with a metal die in the shape of the joint, causing an increase in molecular motion in the region of the joint and an increase in temperature that generates heat in the parts being joined. The parts melt in the joint region, allowing molecular diffusion across the joint interface and weld formation after cooling. Commonly used for sealing polar plastic sheets and films. Also called high frequency welding or heat sealing. Also called RF welding.

random block copolymer A copolymer in which segments of a material, such as ethylene propylene rubber (EPR), are distributed through a random copolymer structure that consists of alternating monomeric units. *See also* block copolymer, random copolymer, homopolymer.

random copolymer A copolymer with alternating segments of two monomeric units, such as propylene and ethylene. Segments can consist of a single monomer or multiple monomers; the two monomers are copolymerized together in the reactor. *See also* block copolymer, random block copolymer, homopolymer

recommended processing time *See processing time.*

recommended screw speed Recommended speed of the extruder screw in plastic processing.

relative humidity The ratio of the actual vapor pressure of the air to the saturation vapor pressure. Also called RH.

relative viscosity The ratio of solution viscosity to the viscosity of the solvent. Also called viscosity ratio, RV.

replaceable tip In ultrasonic welding, a machined titanium forming tool threaded to attach to a horn. Commonly used in ultrasonic staking and spot welding.

resin *See polymer.*

resistance to cracking *See cracking.*

resistance to tear propagation *See tear propagation resistance.*

resistance welding A method for joining plastics, composites, and metals in which heat is generated by application of an electric current to a conductive heating element placed at the joint interface. Thermoplastic material at the joint interface melts and fuses, forming a weld. Thermosets, composites, and metals require a thermoplastic interlayer for bonding. The conductive heating element is usually stainless steel or carbon fiber prepreg and remains in the joint after welding.

RF welding *See radio frequency welding.*

RH *See relative humidity.*

rigid thermoplastic polyurethanes Rigid thermoplastic polyurethanes are not chemically crosslinked. They have high abrasion resistance, good retention of properties at low temperatures, but poor heat resistance, weatherability and resistance to solvents. Rigid thermoplastic polyurethanes are flammable and can release toxic substances. Processed by injection molding and extrusion..

riveting An assembly process in which a short rod with a head on one side is inserted into a preformed hole in two or more parts. The straight end is then pressed or hammered in order to form another head.

Rockwell A *See Rockwell hardness.*

Rockwell E *See Rockwell hardness.*

Rockwell hardness A number derived from the net increase in the depth of impression as the load on an indenter is increased from a fixed minor load (10 kgf) to a major load and then returned to the minor load. This number consists of the number of scale divisions (each corresponding to 0.002 mm vertical movement of the indenter) and scale symbol. Rockwell scales, designated by a single capital letter of English alphabet, vary depending on the diameter of the indenter and the major load. For example, scale A indicates the use of a diamond indenter and major load 60 kgf, E — 1/8" ball indenter and 100 kgf, K — same ball and 150 kgf, M — 1/4" ball and 100 kgf, R — 1/2" ball and 60 kgf. The hardness increases in the order of R, M, K, E, and A scales. Also called Rockwell R, Rockwell M, Rockwell K, Rockwell E, Rockwell A.

Rockwell K *See Rockwell hardness.*

Rockwell M *See Rockwell hardness.*

Rockwell R *See Rockwell hardness.*

room temperature vulcanizing silicone Silicone that is vulcanized or cured at room temperature by a chemical reaction. Room temperature vulcanizing is commonly used for silicones and other thermoset elastomers. Also called RTV silicone.

rotational welding *See spin welding.*

RTV silicone *See room temperature vulcanizing silicone.*

rubber *See thermosetting elastomer.*

RV *See relative viscosity.*

S

SAN *See styrene acrylonitrile copolymer.*

screw speed *See recommended screw speed.*

seal initiation temperature The lower limit of a heat-seal temperature range at which a thermoplastic material such as film is beginning to fuse and adhere to itself or other thermoplastic materials.

secant modulus The slope of a line drawn from the origin to a point on the stress-strain curve for a material that corresponds to a particular strain. Used in designing parts subjected to short-term, infrequent, intermittent stress for plastics in which the stress-strain curve is nonlinear.

self-reinforcing plastics Plastics with densely packed, fibrous polymer chains. Liquid crystal polymers are called self-reinforcing plastics.

self-tapping screw A method of mechanically fastening two plastic parts together in which screws inserted into a pilot hole form mating threads in the plastic part. Self-tapping screws can be either thread-forming or thread-cutting. See also thread forming screw, thread cutting screw.

semicrystalline plastic A plastic material characterized by localized regions of crystallinity. Also called crystalline plastic. See also amorphous plastic.

shear Displacement of a plane of a solid body parallel to itself, relative to other parallel planes within the body; deformation resulting from this displacement.

shear joint A joint design used in welding in which the thermoplastic parts melt in a telescoping action due to a small interference in one of the mating parts.

shear strain The tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body. See also strain, tensile strain, flexural strain, compressive strain.

shelf life Time during which a physical system such as material retains its storage stability under specified conditions. Also called storage life.

Shore A *See Shore hardness.*

Shore D *See Shore hardness.*

Shore hardness Indentation hardness of a material as determined by the depth of an indentation made with an indenter of the Shore-type durometer. The scale reading on this durometer is from 0, corresponding to 0.100" depth, to 100 for zero depth. The Shore A indenter has a sharp point, is spring-loaded to 822 gf, and is used for softer plastics. The Shore B indenter has a blunt point, is spring-loaded to 10 lbf, and is used for harder plastics. Also called Shore D, Shore A.

short glass fiber *See chopped glass fiber.*

shrinkage Contraction of a material upon cooling as in molding of metals or plastics or upon drying as in wet processing of textiles. See also mold shrinkage.

SI *See silicone.*

silicone Silicones are polymers, the backbone of which consists of alternating silicon and oxygen atoms. Pendant organic groups are attached to silicon atoms. They are usually made by hydrolyzing chlorosilanes, followed by polycondensation and crosslinking. Depending on the degree of crosslinking and the nature of pendant groups, silicones can be liquid, elastomeric, or rigid. Liquid silicones or silicone fluids such as dimethylsiloxane have very good antiadhesive properties, lubricity, resistance to heat and chemicals and are used as release agents, surfactants, and lubricants in plastics. As lubricants they improve wear resistance of plastics. Silicone elastomers, or rubbers, have high adhesion, resistance to compression set, flexibility, good dielectric properties, weatherability, low flammability, good moisture barrier properties, and thermal stability, but somewhat low strength. Optically clear grades are available. Processed by coating and injection molding. Used as optical fiber coatings, electronic

connector encapsulants, printed circuit board coatings, seals, diaphragms, fabric coatings, medical products, adhesives, sealants, and glazing compounds. Rigid silicone resins offer good flexibility, weatherability, dirt release properties, dimensional stability, and are stronger and harder than silicone rubbers. The resins are attacked by halogenated solvents. Processed by coating, casting, injection molding, compression molding, and transfer molding. Used as coatings, adhesives, sealants, bonding agents, and molded parts. Also called siloxane, silicone rubber, silicone plastic, silicone fluid, SI, polysiloxane.

silicone fluid *See silicone.*

silicone plastic *See silicone.*

silicone rubber *See silicone.*

siloxane *See silicone.*

sink mark A shallow depression on the surface of an injection molded part. Usually caused by collapse of the part surface following local internal shrinkage after the gate seals. Frequently occurs on the part face opposite to a face in which the section thickness increases, as in a rib. Also called shrink mark, heat mark.

sliding velocity The relative speed of movement of one body against the surface of another body (counterbody) without the loss of contact as in a sliding motion during wear and friction testing of materials. In the sliding motion, the velocity vectors of the body and the counterbody remain parallel and should be unequal if they have the same direction.

slip agent A material such as erucamide or oleamide (modified fatty acid esters) that provides surface lubrication to films and sheets during and immediately after processing. Slip agents reduce sticking of the plastic to itself and facilitate processing on high speed processing equipment.

snap fit A method of mechanical fastening in which two plastic parts are joined by an interlocking configuration that is molded directly into the parts. A protrusion molded into one part, such as a hook or bead, is briefly deflected during assembly and engages a depression or undercut molded into the other part. The joint is usually stress-free after joining. Snap-fit design is important in proper functioning of the snap-fit. Cantilever snap-fits are the most common; other types of snap-fits include annular and torsional.

snap-on connection A type of snap-fit connection in which one part is snapped onto another part, such as a lid on a container. Usually used with rounded parts.

softening point Temperature at which the material changes from rigid to soft or exhibits a sudden and substantial decrease in hardness.

solubility The solubility of a substance is the maximum concentration of a compound in a binary mixture at a given temperature forming a homogeneous solution. Also called dissolving capacity.

solubility parameter Solubility parameter characterizes the capacity of a substance to be dissolved in another substance, e.g., of a polymer in a solvent. It represents the cohesive energy of molecules in a substance and determines the magnitude and the sign of the heat of mixing

two substances in given concentrations. The magnitude and the sign of the heat of mixing determine the sign of the free energy of mixing. The solution occurs when the sign of the free energy of mixing is negative.

solvent bonding A method of joining two thermoplastics by application of a solvent to soften the part surfaces. Softening the polymer increases the movement of polymer chains, allowing them to intermingle at the joint interface. Adhesion occurs after solvent evaporation. Solvent application must be carefully controlled for optimal joint strength and to avoid damage to the part. Also called solvent fusion.

solvent fusion *See solvent bonding.*

specific heat capacity The quantity of heat per unit mass or volume per unit temperature rise, required to increase the temperature of a specimen without change of phase.

spherulite In plastics, a rounded aggregate of radiating lamellar crystals with amorphous material between the crystals. Has the appearance of a pom-pom. Spherulites exist in most crystalline plastics and usually impinge on one another to form polyhedrons. Range in size from a few tenths of a micron in diameter to several millimeters.

spin welding A method used for joining cylindrical thermoplastic parts. Frictional heat develops as one part spins against the other, stationary part, resulting in melting at the joint interface. Spinning is then stopped, and the parts are held together under pressure until cool. Also called friction welding. Also called rotational welding. See also vibration welding.

spun bonded fiber process A one-step process for manufacturing nonwoven fabric from plastic resin. Extruded continuous filaments are stretched and oriented using a high velocity stream of heated air; fabric is formed by blowing the fibers onto a mesh belt, forming a web that is then stabilized. Spun bonding is a type of air attenuated fiber process. It is used in producing sanitary products and geotextiles. See also melt blown fiber process.

stability Resistance to degradation or deterioration from any of a number of conditions (heat, moisture, exposure to chemicals, prolonged storage, etc.). Also called durability. See also stability.

staking In part assembly, a process in which a thermoplastic stud protruding out of the parts being joined is made to soften and flow, forming a head that locks the parts together. Flow can occur as a result of heat or pressure. An alternate form of staking occurs when a thermoplastic is forced to cold flow around a metal insert placed into a plastic boss, locking the insert in place.

staple fiber *See fiber staple.*

static coefficient of friction The ratio of the force that is required to start the friction motion of one surface against another to the force, usually gravitational, acting perpendicular to the two surfaces in contact.

stereochemistry The three-dimensional structure or spatial arrangement of atoms in a molecule.

stereospecific catalyst A catalyst, such as an organometallic metallocene or Ziegler-Natta catalyst, which provides control of the molecular structure of the polymer during polymeriza-

tion, resulting in a polymer with a specific geometrical arrangement of molecules. See also catalyst.

stereospecific plastic A plastic, such as polypropylene, in which the molecular structure has a definite orderly arrangement. Atoms are in fixed positions in geometrical space instead of randomly arranged.

stereospecific reaction A reaction in which molecules with the same molecular structure but different stereochemical structures form stereochemically different products. See also stereochemistry.

steric hindrance A spatial arrangement of the atoms of a molecule that blocks a reaction of the molecule with another molecule.

Sterilization Process of killing of all microorganisms, including spores, on or in an object by chemical or physical means.

storage life *See shelf life.*

strain The per unit change, due to force, in the size or shape of a body referred to its original size or shape. Note: Strain is nondimensional but is often expressed in unit of length per unit of length or percent. Also called mechanical strain. See also flexural strain, compressive strain, tensile strain.

stress cracking Appearance of external and/or internal cracks in the material as a result of stress that is lower than its short-term strength.

stress decrease *See stress relaxation.*

stress relaxation Time-dependent decrease in stress in a solid material as a result of changes in internal or external conditions. Also called stress decrease.

stress whitening The appearance of white regions in a thermoplastic material due to stretching the plastic near its yield point. White regions indicate high stress and irreversible initial damage to the material that can ultimately lead to failure.

stretch blow molding *See blow molding, stretch.*

styrene (C₆H₅CH=CH₂) A colorless, oily liquid with a strong odor. Boils at 145.2°C (293.4°F); freezes at -30.63°C (-23.13°F). Soluble in alcohol and ether; insoluble in water. Polymerizes rapidly when exposed to heat, light, or a peroxide catalyst; polymerization may become explosive. Toxic by ingestion and inhalation; its TLV is 50 ppm in air. Moderate fire risk; autoignition temperature is 490°C (914°F); explosive limit in air is 1.1–6.1%. Derived from reaction of ethylene and benzene in the presence of aluminum chloride to form ethylbenzene, followed by catalytic dehydrogenation at 630°C (1166°F). Used in the production of polystyrene, styrene-butadiene rubber (SBR), acrylonitrile-butadiene-styrene (ABS), and styrene-acrylonitrile (SAN) resins; copolymers, rubber-modified polystyrene, styrenated polyesters, and protective coatings. Also called vinylbenzene, phenylethylene.

styrene acrylonitrile copolymer Thermoplastic copolymers of about 70% styrene and 30% acrylonitrile with higher strength, rigidity, and chemical resistance than polystyrene. Characterized by transparency, high heat deflection properties, excellent gloss, hardness, and dimensional stability. Have low continuous service temperature (185°F) and impact strength. Processing is accomplished by injection,

tion molding, extrusion, injection-blow molding, and compression molding. Used in appliances (refrigerator shelves), housewares, instrument lenses for automobiles, medical devices, and electronics (cassette parts). Also called SAN.

styrene butadiene block copolymer This thermoplastic block polymer is amorphous and is composed of alternating block structures of butadiene and styrene. The butadiene blocks impart toughness and impact resistance to the plastic. The styrene blocks provide thermoplasticity, rigidity, high gloss, and compatibility with other styrenic resins. These polymers exhibit low gel content, water absorption, and mold shrinkage, as well as ease of processing. They may be used in food and drink containers, display containers, toy parts, blister packs, and shrink wrap. Also called styrene butadiene block polymer, butadiene styrene block polymer.

styrene butadiene copolymer A family of thermoplastic copolymers that are comprised of over 50% styrene. They are transparent, have high toughness, are easily processed, and have a low cost. They can be processed by sheet extrusion, injection molding, thermoforming, and blow molding, typically at temperatures between 380 and 450°F. When blended with general purpose polystyrene, applications include disposable packaging, blister packs, and other display packaging. Molded applications include medical devices, parts for toys, display boxes and racks, and office articles. Film applications include wraps.

styrene maleic anhydride copolymer SMA copolymers are thermoplastics prepared by copolymerization of styrene with maleic anhydride. Using butadiene as a third monomer or alloying with ABS results in impact versions of SMA. SMA have high thermal stability and good adhesion, but limited chemical resistance and resistance to UV light. Impact SMA have good impact strength. Processed by injection molding, extrusion, and foam molding. Used in automotive parts such as consoles, small appliances, door panels, pump components, and business machines. Also called SMA.

styrene methyl methacrylate butadiene copolymer A polymer of styrene, methyl methacrylate, and butadiene.

styrene plastic *See styrenic resin.*

styrene resin *See styrenic resin.*

styrenic plastic *See styrenic resin.*

styrenic resin Styrenic resins are a class of thermoplastics prepared mainly by free-radical homopolymerization of styrene or copolymerization of styrene with other unsaturated monomers. The most important families of this class are ABS plastics, polystyrene, styrene maleic anhydride copolymer, and styrene acrylonitrile copolymers. The properties of styrenic resins vary widely with molecular structure, some attaining the high performance level of engineering plastics. Processed by blow and injection molding, extrusion, thermoforming, film techniques, and structural foam molding. Used very heavily in automotive parts, household goods, packaging, films, tools, containers, and pipes. Also called styrenic plastic, styrene resin, styrene plastic, ASR, advanced styrenic resin.

styrenic thermoplastic elastomer These thermoplastic elastomers are comprised of linear or branched copoly-

mers containing polystyrene end blocks and elastomer (e.g., isoprene rubber) middle blocks. The elastomers have hardnesses ranging from 28 to 95 Shore A, tensile strengths from 300 to 5000 psi, and elongation from 250 to 1300%. They also retain their flexibility to temperatures as low as -112°F and have good dielectric properties and hydrolytic stability. They are processable by injection and blow molding and extrusion. Uses include adhesives, coatings, sealants, impact and asphalt modifiers, soles, medical devices, tubing, cable insulation, and automotive parts. Also called thermoplastic styrenic rubber, styrenic TPE, styrenic thermoplastic rubber.

styrenic thermoplastic rubber *See styrenic thermoplastic elastomer.*

styrenic TPE *See styrenic thermoplastic elastomer.*

sulfide adhesive *See polysulfide adhesive.*

surface grafting In adhesive bonding, a surface preparation technique in which a chemical species, such as vinyl acetate monomer, is grafted onto the substrate surface. Commonly used to graft vinylic compounds onto polyolefins.

surface roughening In adhesive bonding, a commonly used surface preparation technique in which the substrate surface is mechanically abraded. The roughened surface increases bondability by dramatically increasing the number of sites available for mechanical interlocking.

surface roughness The closely spaced unevenness of a solid surface (pits and projections); can be quantified by various methods, e.g., by using a profilometer in coatings.

surface tack Stickiness of a surface of a material such as wet paint when touched.

surface tension The surface tension is the cohesive force at a liquid surface measured as a force per unit length along the surface or the work which must be done to extend the area of a surface by a unit area, e.g., by a square centimeter. Also called free surface energy.

syndiotactic A polymer molecule in which pendant groups and atoms attached to the main chain alternate regularly on opposite sides of the polymer chain.

synergistic effect The boosting effect of one substance on the property of another so that the total effect of both substances in a mixture is greater than the sum of the effects of each substance individually, such as synergistic effect of zinc bis(dibutylthiocarbamate) on the UV absorption by zinc oxide.

synthetic polymer *See polymer.*

synthetic resin *See polymer.*

synthetic rubber *See thermosetting elastomer.*

T

Taber abrasion resistance The weight loss of a plastic or other material specimen after it was subjected to abrasion in Taber abraser for a prescribed number of specimen disk rotations, usually 1000. Taber abraser consists of an idling abrasive wheel, designated depending on the type and grit of the abrasive used as CS-10F, H 22, etc., and a rotary disk with the specimen mounted on it. The load is

applied to the wheel. The produced motion simulates that of rolling with slip.

tack *See tackiness.*

tackiness Pull-resistance exerted by a material adhering completely to two separating surfaces; slight stickiness of the surface of a coating, apparent when it pressed with the finger, a characteristic of cure. Also called tack.

talc Talc is a filler made by dry or wet grinding of mineral magnesium silicate. Talc improves stiffness, dimensional stability, flexural modulus, creep resistance, flow, surface smoothness, moisture resistance, tensile strength, and wear resistance of plastics. It also increases heat deflection temperature and decreases vapor permeability. Can be used as a film antiblock agent. Used mainly in polypropylene but also in thermoplastic and unsaturated polyesters and epoxy resins at low levels. Surface-modified grades are available.

tan delta *See dielectric dissipation factor.*

tautomeric Pertaining to tautomerism, i.e., isomerism in which migration of a hydrogen atom results in two or more structures, called tautomers that are in equilibrium. For example, enol and keto tautomers of acetoacetate.

tapping The process of forming threads in the walls of a circular pilot hole in a plastic, metal, or similar material. See also self-tapping screws.

tear propagation force *See tear propagation resistance.*

tear propagation resistance The force required to propagate a slit in a flexible plastic film or thin sheeting at a constant rate of loading, calculated as an average between the initial and the maximum tear-propagation forces. Also called tear propagation force, resistance to tear propagation.

tearing energy Tearing energy is a function of strain energy density and crack length, often expressed in kN/m. Plots of tearing energy vs. fatigue crack growth rate are used to characterize the kinetics of fatigue crack extension in rubbers, which do not obey the classical theory of elasticity. Also called tearing energy parameter.

tearing energy parameter *See tearing energy.*

tensile elongation *See elongation.*

tensile fatigue Progressive localized permanent structural change occurring in a material subjected to cyclic tensile stress that may culminate in cracks or complete fracture after a sufficient number of cycles. See also fatigue, flexural fatigue.

tensile heat distortion temperature *See heat deflection temperature.*

tensile properties Properties describing the reaction of physical systems to tensile stress and strain.

tensile strain The relative length deformation exhibited by a specimen subjected to tensile force. See also compressive strain, flexural strain, shear strain, strain.

tensile strength The maximum tensile stress that a specimen can sustain in a test carried to failure. Note: The maximum stress can be measured at or after the failure or reached before the fracture, depending on the viscoelastic behavior of the material. Also called ultimate tensile strength, tensile ultimate strength, tensile strength at break.

tensile strength at break The maximum load per original minimum cross-sectional area of the plastic specimen in tension within the gage length when the maximum load corresponds to the break point. Measured according to ASTM D638. See also tensile strength.

tensile strength at yield The maximum load per original minimum cross-sectional area of the plastic specimen in tension within the gage length, when the maximum load corresponds to the yield point. Measured according to ASTM D638.

tensile stress The force related to the smallest original cross-section of the specimen at any time of the test.

tensile ultimate strength *See tensile strength.*

TEO *See olefinic thermoplastic elastomer.*

terephthalate polyester A thermoset unsaturated polyester based on terephthalic anhydride. Also called terephthalic polyester, polyester terephthalate.

terephthalic polyester *See terephthalate polyester.*

tertiary hydrogen In an organic molecule, a hydrogen atom attached to a carbon atom that is also attached to three other carbon atoms, as in the hydrogens of the pendant methyl group of polypropylene.

tetrachloroethylene A colorless, chemically stable and nonflammable liquid with ether odor, $\text{CCl}_2=\text{CCl}_2$. Irritant to skin. Derived by chlorination of hydrocarbons. Used as dry-cleaning solvent and drying agent for electronics.

tetrafluoroethylene-propylene copolymer Thermosetting elastomeric polymer of tetrafluoroethylene and propylene having good chemical and heat resistance and flexibility. Used in auto parts.

tex The basic unit of linear density in textiles, equal to the mass in grams of a fiber with a length of one kilometer. Units are g/km or $\text{g/cm} \times 10^{-5}$. One millitex (mtex) = $\text{tex} \times 10^{-3}$.

textile Pertaining to fibers, yarns, fabric, or materials made from fabrics, in which the properties of the fibers, such as strength and flexibility, are generally retained.

TFE *See polytetrafluoroethylene.*

thermal conductivity The time rate of heat transfer by conduction across a unit area of substance at unit thickness and unit temperature gradient.

thermal expansion coefficient The change in volume per unit volume resulting from a change in temperature of the material. The mean coefficient of thermal expansion is commonly referenced to room temperature.

thermal properties Properties related to the effects of heat on physical systems such as materials and heat transport. The effects of heat include the effects on structure, geometry, performance, aging, stress-strain behavior, etc.

thermal recycling A plastics recycling method in which mixed plastic waste undergoes controlled combustion, producing heat that can be used as a substitute for oil, gas, and coal or for the generation of energy at power plants. See also mechanical recycling, feedstock recycling.

thermal stability The resistance of a physical system such as material to decomposition, deterioration of properties

or any type of degradation in storage under specified conditions. Also called oven stability, heat stability.

thermal treatment In adhesive bonding, a surface preparation technique in which the substrate surface is oxidized by exposure to a blast of hot air (~500 °C). Oxidation proceeds by a free radical mechanism and introduces carbonyl, carboxyl, amide, and some hydroperoxide functional groups to the part surface, accompanied by chain scission and some crosslinking. Commonly used for polyolefins, thermal treatment increases wettability and interfacial diffusivity.

thermoforming The process of heating a thermoplastic sheet to a point at which it softens and flows, then applying differential pressure to make the sheet conform to the shape of a mold or die.

thermoplastic Thermoplastics are resin or plastic compounds which, after final processing, are capable of being repeatedly softened by heating and hardened by cooling by means of physical changes. There are a large number of thermoplastic polymers belonging to various classes such as polyolefins and polyamides. Also called thermoplastic resin.

thermoplastic elastomer Polymers and blends that resemble vulcanized rubbers in that they can be deformed significantly at room temperature and return to their original shape after the stress has been removed, but are true thermoplastics that undergo normal plastic flow when heated in uncured state. The thermoplastic elastomers usually consist of hard and soft domains and can be of many chemical types, e.g., olefinic, urethane, polyester, polyamide, and styrenic. The properties of thermoplastic elastomers vary widely but all exhibit good impact strength and toughness. They are processed mainly by (co)extrusion and (co)molding. Uses include automotive parts, wire and cable insulators, adhesives, footwear, and mechanical goods. Also called TPV, TPEL, TPE, thermoplastic rubber.

thermoplastic olefin A blend of a polyolefin and crosslinked or noncrosslinked ethylene propylene rubber (EPR) or ethylene propylene diene monomer (EPDM) produced by compounding or during polymerization in the reactor. An olefin and a noncrosslinked EPR or EPDM is sometimes referred to as a thermoplastic olefin; in this case, the combination of an olefin and crosslinked EPR or EPDM is referred to as a thermoplastic vulcanizate. See also thermoplastic vulcanizate, thermoplastic elastomer.

thermoplastic olefinic rubber See *olefinic thermoplastic elastomer*.

thermoplastic polyolefin rubber See *olefinic thermoplastic elastomer*.

thermoplastic polyurethanes A class of polyurethanes including rigid and elastomeric polymers that can be repeatedly made soft and pliable on heating and hard (flexible or rigid) on subsequent cooling. Also called TPUR, TPU.

thermoplastic resin See *thermoplastic*.

thermoplastic rubber See *thermoplastic elastomer*.

thermoplastic vulcanizate A blend of a polyolefin and crosslinked ethylene propylene rubber (EPR) or ethylene propylene diene monomer (EPDM). See also thermoplastic olefin, thermoplastic elastomer.

thermoset Thermosets are resin and plastic compounds which, after final processing, are substantially infusible and insoluble. Thermosets are often liquids at some stage in their manufacture or processing and are cured by heat, oxidation, radiation, or other means often in the presence of curing agents and catalysts. Curing proceeds via polymerization and/or cross-linking. Cured thermosets cannot be resoftened by heat. There are a large number of thermosetting polymers belonging to various classes such as alkyd and phenolic resins. Also called thermosetting resin, thermoset resin.

thermoset resin See *thermoset*.

thermosetting elastomer A large class of polymers that can be stretched at room temperature to at least twice their original length and, after having been stretched and the stress removed, return with force to approximately their original length in a short time. To attain this elastic property the rubbers must be crosslinked or vulcanized, usually by heating in the presence of various crosslinking agents and catalysts. There are natural and synthetic rubbers. The most important synthetic rubber families are olefinic rubbers, dienic rubbers (nitrile, butadiene, neoprene), silicone rubbers, and urethane rubbers. Used often as impact modifiers/fillers in plastics. Also called synthetic rubber, rubber.

thermosetting resin See *thermoset*.

thermotropic A material in which the shape and packing of the macromolecules is affected by temperature.

thread-cutting screw A type of self-tapping screw that has a sharp cutting edge. Thread-cutting screws remove plastic chips as the screw is inserted, so that internal stresses produced are low. Only minimum reassemblies are possible. See also self-tapping screw.

thread-forming screw A type of self-tapping screw that forms threads by displacing and deforming plastic material, which then flows around the screw head. No material is removed, and large internal stresses are produced in the plastic. See also self-tapping screw.

threaded mechanical insert A metal, self-threading insert with an exterior locking feature for anchorage in the part to be joined. The threaded interior of the insert allows for repeated assembly and disassembly. Threaded mechanical inserts provide high strength joining of plastic parts with low stress.

through transmission infrared welding An infrared welding method in which infrared radiation is transmitted through a part composed of a polymer that does not absorb infrared energy to the other part, composed of a polymer that does absorb infrared energy, at the weld interface. Heat builds up in the absorbing polymer and is transferred to the nonabsorbing polymer through conduction, causing melting at the weld interface. Parts flow together to form a weld. Also called TTIR.

Ti See *titanium*.

tie layer A material used to provide adhesion between layers in applications such as coextrusion, laminating, and coinjection.

tinging strength Tinting strength is the power of a pigment or color to change the color of another pigment or color.

titanium High strength, stiffness, good toughness, low density, good corrosion resistance, nonmagnetic, good heat-transfer and acoustic properties. Commercially pure titanium used primarily for corrosion-resistant service (tanks, heat exchangers, reactor vessels for desalination, chemical processing, or power-generation plants prosthetic devices), titanium alloys for structural, strength-efficient applications (aerospace industry most prominent) from cryogenic to high temperatures, Ti-6Al-4V being the most widely used. Used in manufacturing horns and boosters for ultrasonic welding of plastics. Strength efficiency, fatigue and creep resistance, fracture toughness, weldability, and formability are determined by the alloy chemical composition and microstructure (alpha, beta, or alpha-beta), the latter controlled by composition and heat treatment (annealing or solution treatment and aging). Ti-Al-V and Ti-Al-Sn-base alloys are used in gas turbine, aerospace, marine, and other high-performance applications; titanium beta alloys are ideal spring materials; optic-system support structures (surveillance and guidance for aircraft and missiles) use titanium alloys because their thermal expansion coefficient closely matches that of the optics. Also called Ti.

titanium dioxide Titanium dioxide is a white pigment with high hiding power, used widely in thermosets and thermoplastics. It is also used as a matting agent in nylons and polyesters. The rutile form has higher hiding power than the anatase form and both are chemically inert and resistant to yellowing, blooming, and heat.

toluene (C₆H₅CH₃) A colorless liquid with an aromatic odor. Boils at 110.7°C (231.3°F); freezes at -94.5°C (-138.1°F). Soluble in alcohol, benzene, and ether; insoluble in water. Flammable, fire risk; explosive limit in air is 1.27–7%; autoignition temperature is 536°C (997°F). Toxic by ingestion, inhalation, and skin absorption; TLV is 100 ppm in air. Derived from coal tar or the catalytic reforming of petroleum. Used in high-octane gasolines, explosives (TNT); as a solvent for paints, coatings, gums, resins, oils, rubber, and vinylorganosols; as a chemical intermediate in the production of polyurethanes and polyesters; in saccharin, medicines, dyes, perfumes, detergents, scintillation counters. Also called methylbenzene, phenylmethane, toluol.

toughness Property of a material indicating its ability to absorb energy by plastic deformation rather than crack or fracture.

tow See *fiber tow*.

TPE See *thermoplastic elastomer*.

TPEL See *thermoplastic elastomer*.

TPO See *olefinic thermoplastic elastomer*.

TPU See *thermoplastic polyurethanes*.

TPU See *urethane thermoplastic elastomer*.

TPUR See *thermoplastic polyurethanes*.

TPV See *thermoplastic elastomer*.

transcrystalline growth In adhesive bonding, a surface preparation technique in which adherends are molded

against a high energy metallic substrate that induces transcrystalline growth in the surface regions of the plastic. The formation of crystallites at the surface results in rod-like or columnar spherulites that form inward from the plastic-metal interface; these are thought to strengthen the surface by driving low molecular weight material into the interior. Surface oxidation may also occur, increasing surface reactivity and wettability. The effectiveness of transcrystalline growth is dependent on molding conditions, such as the cooling rate and mold surface. Commonly used for polyolefins, polyamides, and polyurethanes.

transducer A piezoelectric device that converts high-frequency electrical energy into high-frequency mechanical vibrations. See also *piezoelectric*.

transparent Property of a material that transmits a high degree of light, so that objects may be seen clearly through the material.

transparent pigment Pigments such as some organic pigments, having low hiding power. See also *hiding power*.

trichloroethane -1,1,2 (CHCl₂CH₂Cl) A clear, colorless liquid with a sweet odor. Soluble in ethers, alcohols, esters and ketones; insoluble in water. Nonflammable, boils at 113.7°C (236.7°F). Its TLV is 10 ppm in air; it is absorbed by skin. Used in organic synthesis and as a solvent for resins, waxes, oils, fats, and other products. Also called vinyl trichloride.

trichloroethylene (CHCl:CCl₂) A colorless, photoreactive liquid with a slight odor of chloroform. Soluble in common organic solvents; slightly soluble in water. Boils at 86.7°C (188.1°F); not flammable. Does not attack metals, even in the presence of moisture. TLV is 50 ppm in air; toxic by inhalation. Use in cosmetics, drugs, foods is prohibited; use as a solvent is prohibited in some states. Derived from reaction of tetrachloroethane with lime or alkali in the presence of water or from tetrachloroethane thermal decomposition followed by steam distillation. Used in metal degreasing, dry cleaning, diluent in paints and adhesives, cleaning and drying electronic parts, textile processing. Many other uses.

trigger force In ultrasonic welding, the force applied to the parts being joined before ultrasonic vibrations are initiated. Produced by contact of the horn with the parts to be welded. Ultrasonic vibrations are begun after a particular trigger force or distance has been reached by the horn.

trigger point In ultrasonic welding, the point in time during the welding operation when the horn is correctly positioned for the welding process, and ultrasonic vibrations are initiated. Ultrasonic triggering under applied clamp force assures reproducible welds. Reproducible welding cannot be achieved when ultrasonic vibrations are "pre-triggered", and positive controlled clamping cannot be achieved when the horn touches the part while ultrasonically active.

TTIR See *through transmission infrared welding*.

two-part adhesive An adhesive in which the monomer and catalyst or hardener are separate from each other. The two reactive components separately have an indefinite storage life but must be mixed thoroughly before use. Room or elevated temperature cures are possible. Two-part adhesives

include an epoxy monomer and amine hardener; urethanes; and peroxide-initiated adhesive systems such as vulcanized silicone, unsaturated polyesters, and acrylics. See also one-part adhesive.

U

UHMWPE *See ultrahigh molecular weight polyethylene.*

ultimate elongation *See elongation.*

ultimate seal strength Maximum force that a heat-sealed thermoplastic film can sustain in a tensile test without seal failure per unit length of the seal.

ultimate tensile strength *See tensile strength.*

ultrahigh molecular weight polyethylene UHMWPE is a linear carbon-chain polyethylene with molecular weight $(3\text{--}5) \times 10^6$, prepared by Ziegler polymerization of ethylene under special conditions. It has very high wear resistance, toughness, chemical resistance, low friction coefficient, and is self lubricating, but does not melt. Processed by compression molding and ram extrusion from powdered form. Used in bearings, gears, and sliding surfaces in mining and transportation. Also called UHMWPE.

ultrasonic weld force In ultrasonic welding, the force applied to the joint during the welding process. Greater than the trigger force. Intensifies the effectiveness of the colliding molecules in the joint area and provides fast thermal buildup. Must be optimized to the amplitude, generator output power, and geometry of the joint. Generally, high weld force is used with low amplitudes and low weld force with high amplitudes.

ultrasonic welding A joining method for thermoplastics in which energy at ultrasonic frequencies (20–40 kHz) is used to produce low amplitude mechanical vibrations. The vibratory pressure at the joint interface produces frictional heat that melts the thermoplastic parts, allowing them to flow together and bond. Parts may require the use of an energy director in order to concentrate ultrasonic energy. High quality welds are easier to obtain with amorphous than with crystalline thermoplastics.

ultrasound Mechanical vibrations having the same physical nature as sound but with frequencies normally above the range of human hearing.

ultraviolet light *See ultraviolet radiation.*

ultraviolet radiation Electromagnetic radiation in the 40–400 nm wavelength region. Sun is the main natural source of UV radiation on the earth. Artificial sources are many, including fluorescent UV lamps. UV radiation causes polymer photodegradation and other chemical reactions. Note: UV light comprises a significant portion of the natural sun light. Also called UV radiation, UV light, ultraviolet light. See also ultraviolet radiation.

ultraviolet radiation exposure In adhesive bonding, a surface preparation technique in which the substrate is irradiated with high intensity UV light. Exposure to UV radiation results in chain scissions, crosslinking, and oxidation of the polymer surface. The effectiveness of this technique is dependent on the wavelength of radiation used. It is commonly used for polyolefins. Also called UV exposure.

unit cell A small repetitive volume that has all the symmetry of the crystal lattice.

urethane polymer *See polyurethane.*

urethane thermoplastic elastomer These thermoplastic elastomers are comprised of block polyether or polyester polyurethanes containing soft and hard domains or phases. They offer good tensile strength and elongation, service temperatures ranging from 60 to +250°F, excellent adhesion, and a broad hardness range. The ester based elastomers are tougher but will degrade in water in contrast to the ether based elastomers. Both types are somewhat hygroscopic and require drying prior to processing. The processing is carried out by extrusion, injection molding, film blowing, and coating. The molding requires mold release agents. The applications include tubing, water tanks, packaging film, hot-melt adhesives, soles, medical devices, conveyor belts, automotive parts, and cable jacketing. Also called urethane TPE, urethane thermoplastic rubber, TPU, PUR TPE, PU TPE, polyurethane TPE, polyurethane thermoplastic rubber.

urethane thermoplastic rubber *See urethane thermoplastic elastomer.*

urethane TPE *See urethane thermoplastic elastomer.*

UV absorber A low-molecular-weight organic compound such as hydroxybenzophenone derivatives that is capable of absorbing significant amount of radiant energy in the ultraviolet wavelength region, thus protecting the material such as plastic in which it is incorporated from the damaging (degrading) effect of the energy. The absorbed energy is dissipated by UV absorber without significant chemical change via tautomerism of hydrogen bonds. Also called UV stabilizer.

UV exposure *See ultraviolet radiation exposure.*

UV light *See ultraviolet radiation.*

UV radiation *See ultraviolet radiation.*

UV stabilizer *See UV absorber.*

V

van der Waals force A weak attractive forces between molecules, weaker than hydrogen bonds and much weaker than covalent bonds. See also covalent bonds.

vibration welding A technique used for joining thermoplastics in which frictional heat is generated by rubbing the two parts together in a linear or angular motion. When the generated heat melts the two materials at the joint interface, vibration is terminated, and the parts are pressed together and allowed to cool. The vibratory motion is a low frequency (120 Hz, 240 Hz), high amplitude (0.10–0.2 in. or 0.25–0.51 mm of linear displacement), reciprocal motion; a rotary motion is used for circular parts. Vibration welding produces high strength bonds and is particularly suited to large parts or parts with irregular joint surfaces. Also called friction welding. See also spin welding.

Vicat softening point The temperature at which a flat-ended needle of 1 mm² circular or square cross section

will penetrate a thermoplastic specimen to a certain depth under a specified load using a uniform rate of temperature rise. This test (ASTM D1525) is used for thermoplastics such as polyethylene which have no definite melting point. Note: Vicat softening point is determined according to ASTM D1525 test for thermoplastics such as polyethylene which have no definite melting point. Also called Vicat softening temperature.

Vicat softening temperature See *Vicat softening point*.

vinyl ester resin Vinyl ester resins are unsaturated thermosets prepared usually by esterification of glycidyl groups of epoxy resins with unsaturated carboxylic acids. Typically, bisphenol A epoxy resins are treated with methacrylic acid and mixed with styrene reactive diluent. The resins are cured by both peroxide catalyzed addition polymerization of vinyl groups and anhydride crosslinking of hydroxy groups at room or elevated temperatures. Cured bisphenol A vinyl ester resins are characterized by chemical resistance, epoxy novolak vinyl ester resins by solvent and heat resistance, and all vinyl resins in general are tough and flexible in a wide range, but shrink during cure. Processed by filament winding, transfer molding, pultrusion, coating, and lamination. Used in structural composites, coatings, sheet molding compounds, and chemical apparatus. Also called acrylic epoxy resin.

vinyl resin Vinyl resins are a large class of thermoplastics prepared mainly by radical polymerization of vinyl monomers with or without other unsaturated monomers. The most important family of this class are vinyl chloride polymers. Other families are vinyl acetate, vinyl alcohol, vinylidene chloride, and vinyl acetal polymers. Their properties vary widely. In general, they show good weatherability, barrier properties, and flexibility, but are attacked by many solvents and have limited thermal stability. Processed by molding, extrusion, coating, and film techniques. Used very widely, especially as films and in packaging.

vinyl thermoplastic elastomer Vinyl-alloyed thermoplastic elastomer with excellent resistance to ignition, low smoke generation, flexibility at very low temperatures, excellent dielectric properties, good toughness and elongation retention after thermal aging. Processed by extrusion and extrusion coating. Used in cable jacketing and wire coating. Also called vinyl TPE.

vinyl TPE See *vinyl thermoplastic elastomer*.

Vinylidene fluoride hexafluoropropylene copolymer

Thermoplastic copolymer of vinylidene fluoride and hexafluoropropylene. Has better thermal stability; antistatic, dielectric, and antifriction properties; and chemical resistance, but lower mechanical strength at room temperature and creep resistance, compared to incompletely fluorinated fluoropolymers. Processing by conventional thermoplastic techniques is difficult due to its high melt viscosity. Uses include chemical apparatus, containers, films, and coatings. Also called FKM

Vinylidene fluoride hexafluoropropylene tetrafluoroethylene terpolymer Thermosetting elastomeric polymer of vinylidene fluoride, hexafluoropropylene, and tetrafluoroethylene having good chemical and heat resistance and flexibility. Used in auto parts. Also called FKM/TFE

viscoelasticity A property of a material that exhibits both elastic and viscous behavior. Viscoelastic materials have both solid-like characteristics — elasticity, strength, and stability of form — and liquid-like characteristics, such as flow that depends on time, temperature, and stress. All plastics exhibit some degree of viscoelasticity.

viscosity The internal resistance to flow exhibited by a fluid, the ratio of shearing stress to rate of shear. A viscosity of one poise is equal to a force of one dyne/square centimeter that causes two parallel liquid surfaces one square centimeter in area and one centimeter apart to move past one another at a velocity of one cm/second.

viscosity ratio See *relative viscosity*.

volatile compound A material such as alcohol that vaporizes at a relatively low temperature. In a plastic resin, materials that vaporize at or slightly above room temperature.

vulcanizate Rubber that had been irreversibly transformed from predominantly plastic to predominantly elastic material by vulcanization (chemical curing or crosslinking) using heat, vulcanization agents, accelerants, etc.

vulcanizate crosslinks Chemical bonds formed between polymeric chains in rubber as a result of vulcanization.

vulcanization A process in which a rubber or elastomer undergoes a change in its chemical structure, becoming less plastic, more elastic, and more resistant to swelling. An irreversible process accomplished by application of heat or reaction with sulfur or other suitable agents.

W

warpage See *warping*.

warping Dimensional distortion or deviation from the intended shape of a plastic or rubber article as a result of nonuniform internal stress, e.g., caused by uneven heat shrinkage. Also called warpage.

water swell Expansion of material volume as a result of water absorption.

wear Deterioration of a surface due to material removal caused by any of various physical processes, mainly friction against another body.

weld factor The ratio of weld strength to strength outside the welded zone, typically determined by tensile stress tests.

welding amplitude The amplitude used in a welding process. In a vibratory motion such as in vibration or ultrasonic welding, the distance from the equilibrium position to the point of maximum displacement. Varies with welding process used and with the geometry and composition of the parts being welded.

welding by distance A form of heated tool welding in which mechanical stops on the hot tool and holding fixtures are used to control the dimensions of the welded parts. See also welding by pressure, heated tool welding.

welding by pressure A form of heated tool welding in which flow of the molten plastic after heating is regulated by application of specific pressures to the hot tool and parts. Accurate pressure control is necessary, and final part dimensions may vary due to variations in melt thick-

ness and melt viscosity. See also welding by distance, heated tool welding.

welding frequency The frequency used in a welding process. The number of cycles or vibrations per unit of time, usually seconds. Welding frequencies vary depending on the welding process used and on the geometry and composition of the parts being joined. Welding frequencies range from 120 Hz and 240 Hz, used in vibration welding, to 2 to 10 GHz, used in microwave welding. See also frequency.

welding pressure The pressure applied to the parts during welding to hold the parts in place and provide intimate contact for bonding. Welding pressure varies depending on the welding process used and the composition of the parts being joined.

welding time A processing parameter in welding. Definition varies depending on the welding process — can refer to the time vibrations are applied to the parts being joined (ultrasonic welding), the amount of time parts are held together under pressure for cooling and solidification (heated tool welding), or both the spin time and cooling time (spin welding). Welding time is dependent on other processing parameters, such as weld amplitude, weld frequency, weld pressure, power level, temperature, etc.

wettability The rate at which a substance (particle, fiber) can be made wet under specified conditions. See also wetting.

wetting The spreading out (and sometimes absorption) of a fluid onto (or into) a surface. In adhesive bonding, wetting occurs when the surface tension of the liquid adhesive is lower than the critical surface tension of the substrates being bonded. Good surface wetting is essential for high strength adhesive bonds; poor wetting is evident when the liquid beads up on the part surface. Wetting can

be increased by preparation of the part surface prior to adhesive bonding.

wicking The flow of a liquid along a surface through capillary action, resulting from the attraction of the liquid molecules to each other and to the surface.

wollastonite Calcium silicate. Mohs hardness is approx. 5, specific gravity is 2.85. Used in ceramics, paint extenders, welding rod coatings, silica gels, paper coating, mineral wool, soil conditioner. Also used as a reinforcing filler in polyester molding compounds, low density polyethylene, polypropylene, and thermosetting resins. Gives smooth molded surfaces and low water absorption.

Y

yellowing Developing of yellow color in near-white or near-transparent materials such as plastics or coatings as a result of degradation on exposure to light, heat aging, weathering, etc. Usually is measured in terms of yellow index.

Z

Ziegler-Natta catalyst An organometallic catalyst used in the polymerization of polypropylene. Ziegler-Natta catalysts are the most common commercial polymerization catalysts and consist of a transition metal halide, such as titanium trichloride, with an organometallic compound, such as triethylaluminum. They are stereospecific, multi-sited catalysts that produce polymers with a broader molecular weight distribution and higher melting points than metallocene catalysts. See also catalyst, metallocene catalyst, stereospecific catalyst.

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